AN ALGORITHM FOR THE SCHEDULING OF VESSELS THROUGH THE PANAMA CANAL

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THESIS

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An Algorithm For the Scheduling of Vessels

Through the Panama Canal

by

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ABSTRACT

This thesis presents an algorithm for scheduling vessel transits through the Panama Canal together with a compilation of current Marine Traffic Control scheduling practices. The performance of the scheduling algorithm is compared with the results of an actual transit schedule using the Panama Canal Company Marine Traffic Control scheduling objectives and additional measures of effectiveness derived in this paper.

The interaction between these measures of effectiveness is discussed as pertains to their future use in the efficient scheduling of vessels through the canal.

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TABLE I. GLOSSARY[1]

Actual Schedule: The transit schedule contained in a Transit Operations Sheet and used in this paper to compare against the derived schedule.

Available Lane: A lock lane is considered available when the vessel occupying the lane has departed and the vessel's lockage interval has elapsed.

Available Vessel: A vessel is considered available to start transit of the canal when clock time reaches the vessel's ready time. A vessel is considered available to transit a lock if the vessel's loco requirement does not exceed the available lock lane's loco capability and the vessel is next in the order of vessels, timewise, waiting to transit the lock.

Beam Rule (170 foot beam rule): Vessels with a beam width of between 91 feet and 95 feet may meet vessels in the opposite direction in Gaillard Cut if the combined beams of the two vessels do not exceed 170 feet and neither vessel is a Clearcut vessel.

Canal Zone Waters Time: A vessel's elapsed time from the time the vessel has been reported ready for transit until it has completed its transit.

Chamber: The portion of a lock within which a vessel remains while being raised or lowered. Pedro Miguel lock has one chamber per lane,

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[1]Parts of this glossary have been compiled from the Marine Traffic Control Manual, Panama Canal Company, 1971.

Miraflores lock has two chambers per lane and Gatun lock has three chambers per lane.

Clear Channel (CCh): The restriction placed on certain vessels wherein they cannot meet a vessel in the opposite direction in channels at the entrance to the canal.

Clearcut (CC): The restriction placed on certain vessels wherein they cannot meet a vessel in the opposite direction in Gaillard Cut.

Culverts: Large ducts through which water flows to fill or empty lock chambers. Lock transit times depend on assignment of culverts to the lock chambers.

Cut Conflict: A clearcut vessel meets a vessel in the opposite direction in the Cut.

Daylight Transit (DL): The restriction placed on certain vessels wherein they must transit all locks during daylight hours.

Delay Time: The number of minutes elapsed time that a vessel is delayed during transit of the canal.

Derived Schedule: A schedule of vessel transit times resulting from the use of the Scheduling Algorithm.

Double Barrel Operation (DB): The practice of scheduling both lanes of a lock for transits of vessels in the same direction.

Handline: Lockage of a vessel too small to require locomotives.

Initial PM Conflict: The transit time interval of two vessels in opposite directions overlaps at PM lock.

Intransit Time: A vessel's elapsed time to transit the canal from entering the first set of locks until clearing the last set of locks.

Lane: Each lock has parallel sets of chambers providing for two lane operations.

Lock: The structure containing two lanes with one or more sets of chambers in each lane designed for lifting or lowering vessels from one body of water to another.

Lockage: The complete passage of a vessel or group of vessels transiting as a unit through all lock chambers in a lock lane.

Lockage Interval: The elapsed time between the start of lockage of one vessel until the lock lane is available to receive the next vessel.

Lock Dead Time: The number of minutes elapsed time between the completion of the lockage interval of one vessel at a lock lane and the arrival of the next vessel at that lane.

Lock Locomotive Capability: The number of manned locomotives available at each lane of a lock.

Lock Transit Time: The elapsed time between the start and completion of a vessel's lockage.

Locomotives: Electrically-powered engines running on rail tracks along both sides of a lane for the purpose of towing and controlling a vessel throughout its lockage. Vessels may require four, six or eight locomotives depending on size.

PM Conflict: Two vessels in opposite directions scheduled to transit PM lock with overlapping transit time intervals and only one lane available.

Ready Time: The time that an arriving vessel completes customs, quarantine and admeasurement inspections, fueling and cargo transfer and is declared ready for transit.

Regular Lockage: The use of one set of locomotives to handle lockages in a lock lane.

Relay Lockage: The use of two sets of locomotives to handle lockages in a lock lane.

Tandem Lockage: A lockage in which two vessels occupy the same chamber at the same time.

Tie-up: Vessels may be required to delay their transit by tying up to the center approach wall at a lock prior to entering the lock or after completing lockage.

Transit Operations Sheet (TOS): The form which Marine Traffic Control schedulers fill out after the completion of vessel transits for a particular day showing actual vessel transit times through various sections of the canal.

Wires: Each locomotive is secured to the transiting vessel in a lock lane by one or two wires (wire rope). Four to twelve wires may be required on a particular vessel.

I. INTRODUCTION

A. IMPORTANCE OF THE PANAMA CANAL

The Panama Canal Zone is a ten-mile wide strip of land across the Isthmus of Panama ceded in perpetuity to the United States by the government of the Republic of Panama in 1903. The Panama Canal runs through the Canal Zone southward from the Atlantic Coast city of Cristobal to the Pacific Coast city of Balboa.

The importance to United States commerce of the Panama Canal cannot be understated. Approximately 70 per cent of cargoes transiting the Panama Canal either originate in or are destined for the United States. In addition, more than 40 per cent of the ocean trade of South American countries passes through the canal. Finally, the canal is used by almost every country in the world in varying capacities.[2]

The Panama Canal presently averages about 15,000 vessels per year (41 vessels per day) and the future saturation limit of the canal has been estimated to be about 26,800 transits per year (73 vessels per day).[3] Various studies conducted on the world-wide usage of the Panama Canal indicate that saturation of the canal will not occur until 1990 or later.[4] In this regard, the building of a proposed new canal notwithstanding, the Panama Canal will be a viable factor in world commerce, especially on the American continent, for many years to come.

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[2]U.S. Atlantic-Pacific Interoceanic Canal Study Commission, Interoceanic Canal Studies, 1970, p.7.

[3]Ibid., p. 48.

[4]Ibid., p. 21.

B. DESCRIPTION OF THE PANAMA CANAL

The existing Panama Canal consists of short sea-level approaches to an elevated center section formed by the 21 mile long Gatun Lake consisting of fresh water fed by the Chagres River flowing from the interior of the Republic of Panama. The lake is maintained between 81 and 87 feet above sea level depending on the availability of water. This height is the total lift which a vessel must make during the transit of the canal.

On the Atlantic side of the canal is Gatun lock consisting of two parallel lanes with three lift chambers per lane which lift southbound vessels from sea level to Gatun Lake and lower northbound vessels from Gatun Lake to the Atlantic Ocean.

On the Pacific side of the canal are two sets of lock structures. Miraflores lock consists of two parallel lanes with two lift chambers per lane which lift northbound vessels from sea level to Miraflores Lake and lower southbound vessels from Miraflores Lake to the Pacific Ocean. Miraflores Lake is an intermediate body of fresh water which is maintained at an approximate elevation of 54 feet above sea level and is fed by Gatun Lake through Pedro Miguel lock which is the final lock in the canal. Pedro Miguel lock consist of two parallel lanes with one lift chamber in each lane which lifts northbound vessels from Miraflores Lake to Gaillard Cut and lowers southbound vessels from Gaillard Cut to Miraflores Lake.

Gaillard Cut is a seven-mile long , 500 foot wide passage excavated through hilly jungle across the continental divide to connect the Atlantic and Pacific sections of the canal.

A diagram of the 43 mile long canal is provided as Figure 1. This diagram shows a range of transit times for each section of the canal and a range of lockage intervals, the elapsed time between the start of lockage of one vessel until the lock lane is available to receive the next vessel, for each set of locks.

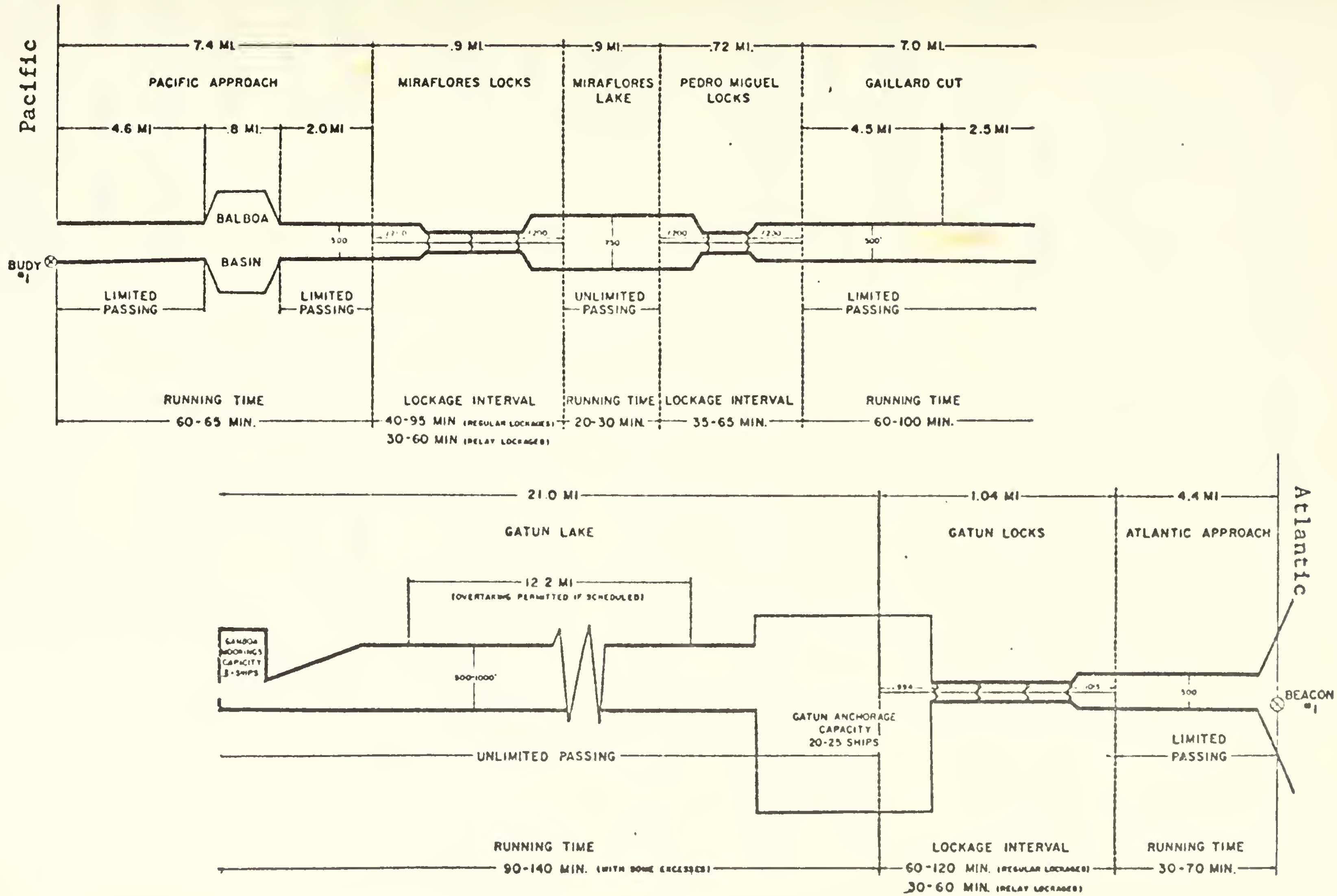
Average Intransit time, a vessel's elapsed time from entering the first set of locks until clearing the last set of locks, is seven hours. Individual vessel Intransit times depend on vessel size and delays encountered while in transit. Canal Zone Waters time, the elapsed time from the time a vessel has been reported ready for transit until it has completed its transit, may vary from 12 to 24 hours for a typical vessel.

C. VESSEL ARRIVAL REQUIREMENTS

Vessels desiring to transit the Panama Canal notify canal authorities 48 hours in advance of their expected arrival time and again when approximately 90 miles distant from Canal Zone jurisdictional waters. This procedure is designed to allow advance preparation of schedules and preliminary planning of daily canal usage.

Upon arrival in Canal Zone waters the vessel is anchored and met by boarding officers for customs and quarantine clearance. In addition, depending on any structural changes subsequent to the vessel's last canal transit, admeasurement personnel determine the need to measure the vessel for determination of toll charges. The entire inspection procedure exclusive of the possible need for admeasurement is accomplished within

Figure 1. Diagram of the Panama Canal[5]



[5] Adapted from a drawing in the Marine Traffic Control Manual, Panama Canal Co., p104.

30 minutes and the vessel is then declared ready for transit unless docking for fuel or cargo transfer is necessary. Depending on transit volume, vessel arrival and ready time, and mix of vessels awaiting transit, the vessel may begin transit immediately or be required to wait at anchor until its turn is reached. Usual delays at anchor while awaiting transit are from four to eight hours although some may be as small as a few minutes to as long as 70 hours.

D. VESSEL SCHEDULING OVERVIEW

Scheduling of all transits through the Panama Canal is presently accomplished manually. Marine Traffic Control Schedulers (MTCS) are tasked with maintaining a projected schedule 36 hours in advance of actual transits and updating and revising this schedule to reflect the actual status of canal operations.

Vessels are normally scheduled on a "first ready, first served" basis with exceptions at the discretion of the MTCS. The MTCS are also constrained by numerous restrictions and requirements placed on transits of vessels due to size, type of cargo and other considerations intended to ensure the safety of all transiting vessels and the canal.

Since the MTCS are normally constrained by the order of vessel arrivals and ready times at the canal there is no real possibility of developing "the" optimal schedule for a particular mix of vessels awaiting transit. However, there are many decisions which must be made during the actual scheduling of vessels in both directions through the various

sections of the canal which can make one schedule better than another for a particular mix of vessels. The difficulty of making these decisions is considerable since the final result of any given decision cannot, in many instances, be known without completing the schedule. There are presently no published procedures for the use of the MTCS in making these decisions. Current Marine Traffic Control practice is to rely on the insight and experience of the schedulers to produce an efficient and practical schedule.

E. OBJECTIVE OF THIS REPORT

This report describes an attempt to develop some practical scheduling guidelines and measures of effectiveness and to provide a written procedure, in the form of an algorithm, for the scheduling of shipping through the Panama Canal.

II. CURRENT VESSEL SCHEDULING PROCEDURES

A. VESSEL SCHEDULING OBJECTIVES

The scheduling objectives under which the Marine Traffic Control Schedulers process traffic through the Panama Canal are:

(1) Obtain maximum lockage capacity in the lock of least capacity consistent with demand.

(2) Obtain the lowest possible Intransit time and Canal Zone Waters time for each vessel.

(3) Maintain a reasonable balance between northbound and southbound shipping transiting the canal.

(4) Process traffic without overtime at the locks as much as possible consistent with demand.

Normally the lock of least capacity is Gatun lock with an average transit time of one hour between vessels in either lane. The first objective may, of course, operate on one of the other sets of locks if a lane is inoperative for maintenance or a casualty or during situations of reduced crewing of locomotives at one of the locks necessitating single lane operation. In general, Marine Traffic Control Schedulers endeavor to maintain the lock of least capacity fully scheduled with no slack or dead time.

In many cases there is a large difference between Instransit time and Canal Zone Waters time for each vessel transiting the canal. Much

of this difference is due to the need to delay some vessels much past their ready times in order to provide a schedule which is better for the majority of vessels. These delays are necessitated by current canal operating conditions and restrictions placed on specific vessels due to safety considerations.

Depending on traffic demand an effort is made to maintain approximately the same number of northbound and southbound vessels transiting the canal in a given scheduling period. The effect of an unbalanced schedule when traffic demand is the same in each direction is obvious. Objective (3) also contributes to obtaining the lowest possible Canal Zone Waters times for each vessel.

Locks are normally manned by sufficient locomotive crews for six locomotives in each lane. Additional personnel are required for the transit of eight-locomotive vessels and are considered overtime crews. In addition, the possibility of securing one lane at a lock when traffic demand permits is also a factor. In-as-much as an inefficient schedule contributes to increased personnel costs due to the need to maintain additional personnel for longer periods than would otherwise be necessary objective (4) is a valid consideration.

B. PANAMA CANAL OPERATING RESTRICTIONS

1. Assignment of Vessel Classes, Restrictions and Requirements

Marine Traffic Control Schedulers operate under the "first ready, first served" rule. However, in scheduling certain classes of vessels,

the time of day of the vessel's transit becomes a factor in its scheduling. In addition, the time of transit of certain portions of the canal for some classes of vessels in relation to the transit of this portion of the canal by other vessels must become a consideration.

Appendix A provides a table of vessel restrictions and requirements for the safe and orderly transit of the canal. Controlling restrictions on vessels are length, beam, draft and type of cargo, with vessels in excess of 1,000 feet in length, 110 feet in beam and 41 feet in draft excluded from transit. These figures are the dimensions of the individual lock chambers of all the locks. Appendix A is utilized by entering the table with vessel length, beam and, in some cases, cargo on board. Operative restrictions and canal transit requirements are listed horizontally across the table with appropriate notes printed below the table. A Clearcut-designated vessel, for example, must not meet other vessels while transiting Gaillard Cut. The Marine Traffic Control Scheduler will schedule the start of this particular vessel based on factors such as the mix of vessels requiring transit, when Gaillard Cut will be available to this vessel for transit with the least disruption of other traffic and lockage requirements of this vessel and other vessels at Pedro Miguel lock.

2. Timing of Vessel Transits

Appendix B provides a table of lockage intervals and transit times for the three locks and other sections of the canal. The table of transit times is entered using vessel beam and draft information and whether the vessel is part of a tandem pair in which two vessels occupy

the same lock chamber at the same time. Marine Traffic Control Schedulers use the times given in Appendix B to schedule individual vessels through each section of the canal.

3. Lockage Procedures

There are two methods of transiting vessels through the locks in the canal. The Regular lockage procedure is a method whereby one set of locomotives controls a vessel's transit through all chambers of the lock. Under Relay lockage procedures two sets of locomotives are required and the vessel is handed off from one set of locomotives to the other in the middle lock chamber. Although an additional set of locomotives is required in order to relay vessels through a lock, two vessels can be in the lock at the same time. Relay lockages are utilized only to transit several vessels in the same direction. Due to the single chamber construction of Pedro Miguel lock, Relay procedures are not utilized at that lock.

Appendix C, Figure 5, depicts the mechanics of the lockage procedure for both Regular and Relay lockages. Tables XII and XIII illustrate the utilization of Appendix B, tables of lockage intervals and transit times, under Regular and Relay lockage procedures respectively. Particular attention should be given to the difference between lockage interval and lock transit time as used in these tables.

4. Locomotive Requirements

Locomotives (locos) are electrically-powered engines which run on rail tracks along both sides of a lock lane. Locos are used to tow and

control vessels while transiting each set of locks since, in most cases, vessels do not use their own propulsion plant while inside a lock chamber. There are normally 19 locos available at each lock, however, the number of locomotive operators assigned varies with traffic intensity and canal operating conditions. The number of manned locos available in a lock lane limits the size of vessel, based on loco restrictions in Appendix A, allowed to transit in that lane as shown in the following table.

TABLE II. LOCOMOTIVE REQUIREMENTS[6]

Type of Lockage	No. of Locomotives in a Lane	Lockage Limitation
Regular	4	Only four locomotive vessels.
Regular	6	All vessels except tandems.
Regular	8	None.
Relay	8	Only four locomotive vessels.
Relay	10	All vessels except tandems or two consecutive six locomotive vessels.
Relay	12	All vessels. Tandems must be followed by a four locomotive vessel.
Relay	16	None.

[6]Compiled from data in the Marine Traffic Control Manual, Panama Canal Company, p. 84.

The number of locomotive operators in one lane may be supplemented by locomotive operators from the other lane. Sufficient time must be alloted in the schedule for this shift to take place. Required time to shift operators is 30 minutes at Gatun lock and 20 minutes at Miraflores and Pedro Miguel locks.

5. Vessel Delay and Tie-Up Restrictions

Once a vessel is intransit in the canal there are only certain areas where a delay to a vessel may be scheduled. These areas are:

a. Balboa basin (limited to two vessels at anchor).

b. Gamboa moorings (three or four vessels).

c. Gatun Lake (25 vessels at anchor).

d. North or South approach walls of any of the three locks (two or three vessels depending on size).

Tie-ups to a lock-lane approach wall can be utilized to delay vessels while awaiting clearance for the Cut or various channels and to make up tandems for lockage. When tie-ups at a lock-lane approach wall are utilized the usage of that particular lock lane is limited to a vessel or vessels already in the lock-lane chambers and proceding in the same direction.

C. CURRENT VESSEL SCHEDULING MECHANICS

There are currently no written procedures for the Marine Traffic Control Schedulers to schedule vessels through the Panama Canal while adhering to the vessel restrictions and canal requirements described above. The

difficulty of making scheduling decisions on the basis of these restrictions and requirements is considerable since the final result of any one given decision by the scheduler cannot, in many cases, be determined without fully completing all or at least a great portion of the schedule. To do this for all possible combinations of vessels requiring transit on a given day in order to arrive at the optimum schedule would be an extremely time-consuming process. Instead, the insight and experience of the Marine Traffic Control Schedulers is relied on to reduce the number of possible alternatives considered and to produce a practical schedule within the scope of the Panama Canal scheduling objectives.

A scheduling form (PanCanal Co. 4374) is utilized by the scheduler to plan his rough schedule of each day's transits through the canal. Using trial and error, the forms, one for northbound vessels and one for southbound vessels, are filled in. During this process changes and alterations to the schedule are made, as necessary, to avoid or eliminate conflicts between vessels. The process is completed when canal capacity is reached or all vessels requiring transit on that particular day are scheduled.

Upon completion of actual vessel transits for a particular day, actual vessel transit times through various portions of the canal are filled in on the Transit Operations Sheet (PanCanal Co. 4344). This form provides a permanent record of vessel transits together with statistics showing individual vessel Intransit times and Canal Zone Waters times.

III. SCHEDULING ALGORITHM

A. INTRODUCTION

In studying the algorithm presented, it is helpful to think of the Panama Canal as divided into three sections created by the physical limitations within the canal and also by the restrictions imposed on vessels transiting the canal. These three sections are; (1) the Miraflores/Pedro Miguel (MF/PM) lock complex including the Pacific Channel, Miraflores Lake and the Gaillard Cut, (2) Gatun Lake, and (3) Gatun lock and the Atlantic Channel. The reasoning behind this division is that vessels which have entered the MF/PM lock complex or the Gatun lock complex are normally constrained to continue transit and clear that section so as not to hold up other shipping. Gatun Lake is a natural unrestricted anchorage which may be utilized to delay northbound vessels prior to transit of the Gatun lock complex.

There are several abbreviations which are used in the algorithm. These are:

1. NB - A vessel which begins transit of the canal at Miraflores lock (northbound direction).
2. SB - A vessel which begins transit of the canal at Gatun lock (southbound direction).
3. Gatun(x/y), MF(x/y), PM(x/y) - Lock locomotive crew availability. The letter x represents the number of locomotive crews available in the east lane and the letter y represents the number of

locomotive crews available in the west lane. For example, MF(6/4) means that the east lane at Miraflores lock has sufficient locomotive crews to transit six-loco vessels and the west lane has sufficient locomotive crews to transit only four-loco vessels.

4. NB(6), NB(4), SB(6), SB(4) - Locomotive requirement for a particular vessel in the direction indicated. For example, SB(4) means that this particular southbound vessel requires four locomotives when passing through a lock lane.

5. NB(CC), SB(CC) - This particular vessel in the direction indicated is restricted to not meeting other vessels in the opposite direction in Gaillard Cut (a "Clearcut" vessel).

6. NB(DL), SB(DL) - This particular vessel in the direction indicated is restricted to not transiting any lock during hours of darkness (a "Daylight" vessel).

7. DB - Refers to double barrel operation at a lock. Two vessels transit the lock at essentially the same time, both in the same direction, in "opposite" lanes.

There are also five terms which are used in the algorithm with which familiarity is necessary. These are:

1. Available lane - A lock lane is considered available when the departing vessel's lockage interval has elapsed.

2. Available vessel - A vessel is considered available to start transit of the canal when clock time reaches the vessel's ready

time. A vessel is considered available to transit a lock if the vessel's loco requirement does not exceed the available lock lane's loco capability and the vessel is next in the order of vessels, time-wise, waiting to transit the lock.

3. Cut conflict - A Clearcut vessel meets a vessel in the opposite direction in the Cut.

4. Initial PM conflict - The transit time interval of two vessels in opposite directions overlaps at PM lock.

5. PM conflict - Two vessels in opposite directions scheduled to transit PM lock with overlapping transit time intervals and only one lane available.

Certain assumptions have been made in this paper in order to produce an algorithm which accurately models the canal under modified operating conditions. After satisfactory testing it is felt that additional constraints can then be built into the algorithm for use under unrestricted canal operating conditions. These assumptions are:

1. The scheduling period for each day's transits commences at midnight or when the first lock at each end of the canal becomes available, whichever is later.

2. At the start of each scheduling period (0000 clock time) only SB vessels from the previous period's transits will be passing through the MF/PM lock complex. Only NB vessels from the previous period's transits will be passing through the Gatun lock complex.

3. Only four and six locomotive vessels are considered.

4. Each lock has either a (6/6) or a (6/4) capability.

5. Clear channel vessels are not considered.

6. Vessel tug requirements are not considered.

7. Tandem lockages are not considered.

8. All vessels are assumed to meet the requirements of the 170 foot beam rule in the Cut. This rule is defined in Table I.

9. Vessels are only allowed to delay in Gatun Lake or by tie-up along lock approach walls.

B. ALGORITHM OVERVIEW

The scheduling algorithm starts with a listing of each vessel desiring transit along with the time each vessel was, or will be, ready to start transit, locomotive requirements, vessel beam width for the purpose of computing transit times, special restrictions and other pertinent facts. From the previous period's schedule the time that each lane in each lock will be available to commence transit of vessels in this scheduling period is noted.

The locomotive capability at each lock lane, based on loco crews available at each lock lane, is then indicated on the NB and SB scheduling forms, in the space provided, for reference by the scheduler when creating the schedule.

The first "available" SB vessel is scheduled through Gatun lock, Gatun Lake, the Cut and through PM lock. "Available" NB vessels are next

scheduled in ready time order, using double barreling procedures when possible, until the current NB being scheduled and thefirst SB vessel scheduled have overlapping transit time intervals at PM lock ("Initial PM conflict").

Once this conflict time has been determined the time that the first NB vessel, scheduled through Gatun Lake, is available at Gatun lock will also have been determined. SB vessels are next scheduled through Gatun lock in ready time order, using double barreling procedures when possible, up to the time that the first NB vessel is available for lockage at Gatun lock.

When this time has been reached NB vessels available in Gatun Lake and SB vessels on the ready time list are scheduled through Gatun lock using a single lane for each direction until the supply of NB vessels in Gatun Lake is exhausted.

At this time there is one NB vessel and the first SB vessel at PM lock and other SB vessels in Gatun Lake available to transit the Cut. The "initial PM conflict" is next resolved between the NB and SB vessels at PM lock. The resolution of the conflict determines lane assignments at PM and MF locks for NB and SB vessels based on the loco requirements of NB vessels ready to start transit of the canal. If the first SB vessel was also involved in a Cut conflict the conflict is now resolved.

Scheduling continues in an iterative process involving the scheduling of vessels through Gatun lock when NB vessels are available in Gatun

Lake for lockage and the scheduling of vessels through the Cut and MF and PM locks when the supply of NB vessels in the lake is exhausted. Conflicts at the Cut or PM conflicts are resolved as they occur.

Once all NB vessels have transited the canal the final step of the algorithm ensures that all SB vessels complete transit.

Flow charts illustrating the relationships among the steps in the algorithm are provided at various points in the algorithm text.

C. SCHEDULING ALGORITHM

1. List all vessels requiring transit in the same direction in the order of their ready times showing ready times, locomotives required, vessel beam width and special restrictions (Clearcut and/or Daylight) for each vessel. From the previous period's schedule note the time that each lane at MF and PM locks will be available to lock NB vessels (start of lockage of the last SB vessel scheduled through each lane plus the lockage interval for that vessel or midnight, whichever is later). Note the time that each lane at Gatun lock will be available to lock SB vessels (start of lockage of the last NB vessel scheduled through each lane plus that vessel's lockage interval or midnight, whichever is later). Designate on the scheduling form for each direction the loco capability of each lane at MF, PM and Gatun locks. Depending on the number of loco crews available at each lock, possible lock lane loco capabilities are either six or four locomotives.

The earliest lane available should be designated as a six-loco lane at each lock if the six-loco lane is not required for transiting the last vessels on the previous period's transit schedule. Go to step 2.

2. Schedule the first available SB vessel on the ready time list through the earliest available lane at Gatun lock and continue this vessel through Gatun Lake, the Cut and PM lock. DL vessels are not considered available for transit until the vessel's transit start time plus channel running time is greater than or equal to the time of daylight. Go to step 3.

3. Commence scheduling available NB vessels in the order of their ready times through MF and PM locks, the Cut and Gatun Lake.
   a. If one lane at MF and at PM is available earlier than the other lane and they are both six-loco lanes, send as many six-loco and four-loco NB vessels as possible through this lane in each lock without violating any vessel ready times. Go to step 3c.
   b. If one lane at MF and at PM is available earlier than the other and they are both four-loco lanes or one is a four-loco lane, send as many four-loco vessels as possible through this lane in each lock without violating any vessel ready times. Go to step 3c.
   c. If both lanes at MF and PM are available at the same time or when both lanes become available, commence double barreling NB vessels through both locks, the Cut and Gatun Lake. Go to step 3d.

d. Stop scheduling NB vessels when the time interval of the NB vessel currently being scheduled overlaps the time interval of the first SB vessel scheduled at PM lock or there is a Cut conflict caused by the first SB vessel being a Clearcut (CC) vessel or by any NB(CC) vessel which the first SB vessel's Cut transit time interval overlaps in the Cut. Go to step 4.

4. Schedule the second and subsequently available SB vessels through Gatun lock and Gatun Lake.

   a. If one lane at Gatun lock is available earlier than the other and it is a six-loco lane, schedule as many six-loco and four-loco vessels as possible through this lane without violating vessel ready times. Go to step 4c.

   b. If one lane at Gatun lock is available earlier than the other and it is a four-loco lane, schedule as many four-loco vessels as possible through this lane without violating any vessel ready times. Go to step 4 c.

   c. If both lanes at Gatun lock are available at the same time or when both lanes become available, commence double barreling SB vessels through both lanes and through Gatun Lake. Go to Step 4d.

   d. Stop double barreling SB vessels at Gatun when the first NB vessel is available to lock at Gatun. Go to step 5.

5. Assign lanes at Gatun lock based on the loco requirements of vessels in each direction available for lockage. Schedule available NB and SB vessels through Gatun lock. Switch lanes as necessary to allow SB vessels to transit Gatun lock without delay due to loco requirements. NB vessels are to take delays in Gatun Lake while awaiting an available lane at Gatun. NB vessels are not to be delayed due to the double barreling of SB vessels at Gatun lock. Stop scheduling SB vessels into Gatun Lake when the last available NB vessel in Gatun Lake has passed through Gatun lock and finished transit or there are no more SB vessels on the ready time list. Go to step 6.

6. a. If both MF and PM are 6/6 assign one lane at each lock to SB vessels and one lane at each lock to NB vessels. If there is a Cut conflict go to step 7, otherwise go to step 10.

   b. If either MF or PM are 6/4 and:

      (1) There are no more NB(6) vessels remaining on the ready time list or NB(6) vessels are not available to start canal transit, assign the four-loco lanes at MF and PM locks to NB vessels and the six-loco lanes to SB vessels. If there is a Cut conflict go to step 7, otherwise go to step 8.

      (2) If NB(6) vessels are available to start canal transit assign the four-loco lanes at MF and PM to SB vessels and the six-loco lanes to NB vessels. If there is a Cut conflict go to step 7, otherwise go to step 9.

7. a. If the NB vessel is a CC vessel and the SB vessel available to transit the Cut is not and:

   (1) There is another NB(CC) vessel available to start transit following this NB(CC) vessel; delay the first NB(CC) vessel by tie-up after transit of PM until 10 minutes prior to the finish of transit at PM lock of the following NB(CC) vessel. Schedule as many available SB vessels through PM to the finish of transit as possible prior to the start of transit of the Cut by the first NB(CC) vessel. Schedule the NB vessels through the Cut and Gatun Lake. Go to step 11.

   (2) Another NB(CC) vessel is not available to start transit. Delay the available SB vessel in Gatun Lake until the NB(CC) vessel transits the Cut. Schedule the NB(CC) vessel through the Cut and Gatun Lake. Schedule the SB vessel through PM lock to the finish of transit. Go to step 11.

b. If the available SB vessel is a CC and the NB vessel is not and:

   (1) If the NB vessel is a DL vessel, delay the SB(CC) vessel in the lake. Schedule the NB vessel through the Cut and Gatun Lake. Go to step 11.

   (2) If the NB vessel is not a DL vessel, delay the NB vessel and any previous NB vessels that had not started transit of the Cut prior to the time the SB(CC) vessel could have started transit. Re-schedule the delayed NB vessels to

provide for delays at either MF or PM locks. If a second SB(CC) vessel is available to transit the Cut at the same time as the first SB(CC) vessel, even if taken out of order of sequence of SB vessels available in Gatun Lake, both CC vessels should transit the Cut at a 10 minute interval. Schedule the SB(CC) vessel(s) through PM lock to the finish of transit. Schedule the NB vessel(s) delayed at MF or PM locks through the Cut and Gatun Lake. Go to step 11.

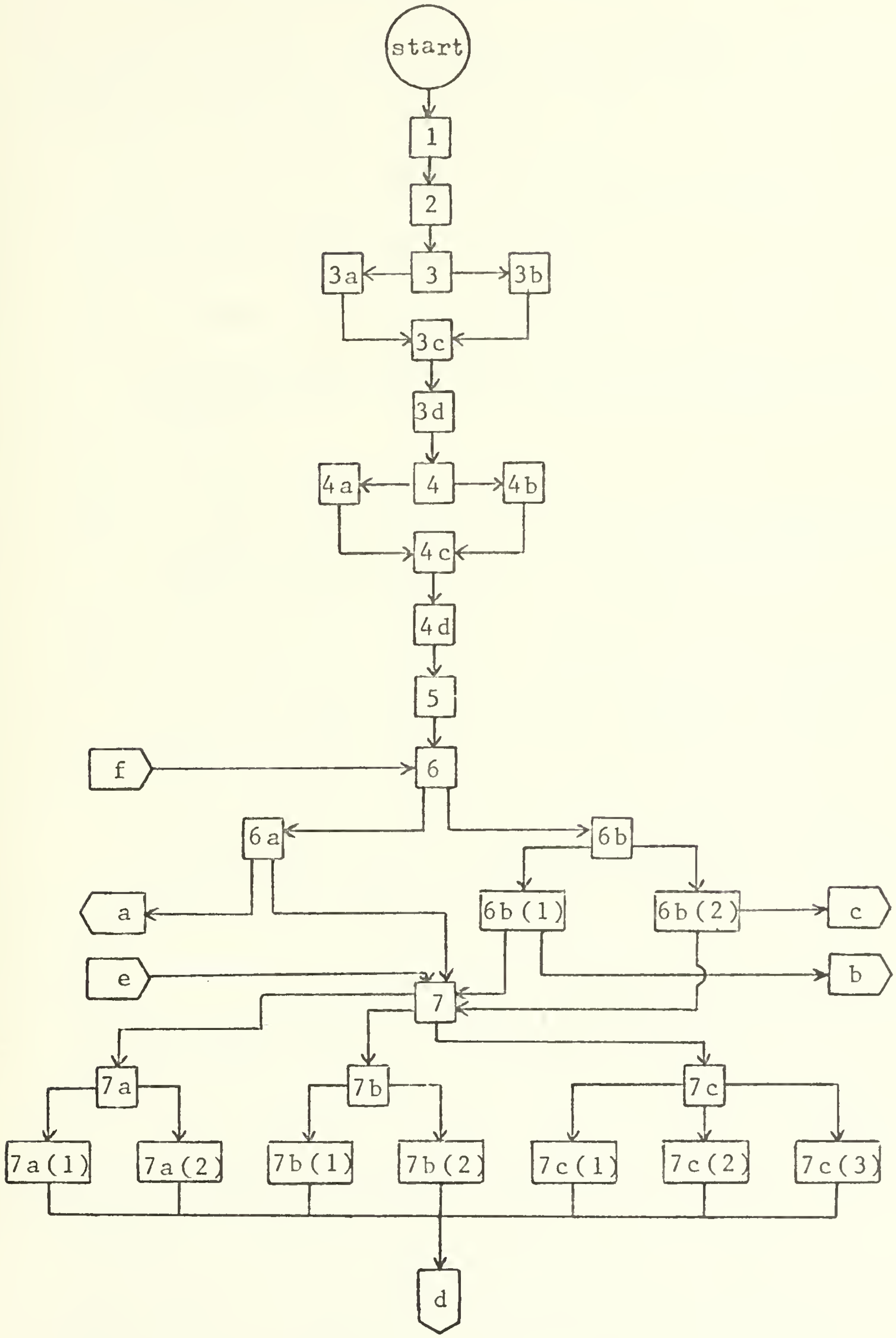
c. If both the NB and SB vessels are CC vessels:

(1) If both vessels have a second CC vessel available for transit delay the first NB(CC) vessel by tie-up after transit of PM lock until 10 minutes prior to the finish of transit at PM of the following CC vessel. Schedule both SB(CC) vessels through the Cut and the finish of transit prior to scheduling the NB(CC) vessels through the Cut and Gatun Lake. Go to step 11.

(2) If only the vessel in one direction has a second CC vessel available to transit, delay the vessel in the opposite direction until the two vessels complete their transit of the Cut. Schedule the SB vessel(s) through to the finish of transit and the NB vessel(s) through Gatun Lake. Go to step 11.

(3) If neither CC vessel has a second CC vessel available to transit delay the SB vessel in Gatun Lake. Schedule the NB vessel through Gatun Lake. Go to step 11.

Figure 2. Algorithm Flow Chart, Part A



8. If SB vessel(s) at PM lock have not yet been scheduled through the finish of transit, do so. Determine the status of NB vessel(s) at PM lock and the next available SB vessel in Gatun Lake.

   a. If there is not a NB vessel at PM lock, go to step 8c. If there is a NB vessel at PM lock and:

      (1) If there is no SB vessel available in Gatun Lake schedule the NB vessel at PM lock through Gatun Lake. Go to step 11.

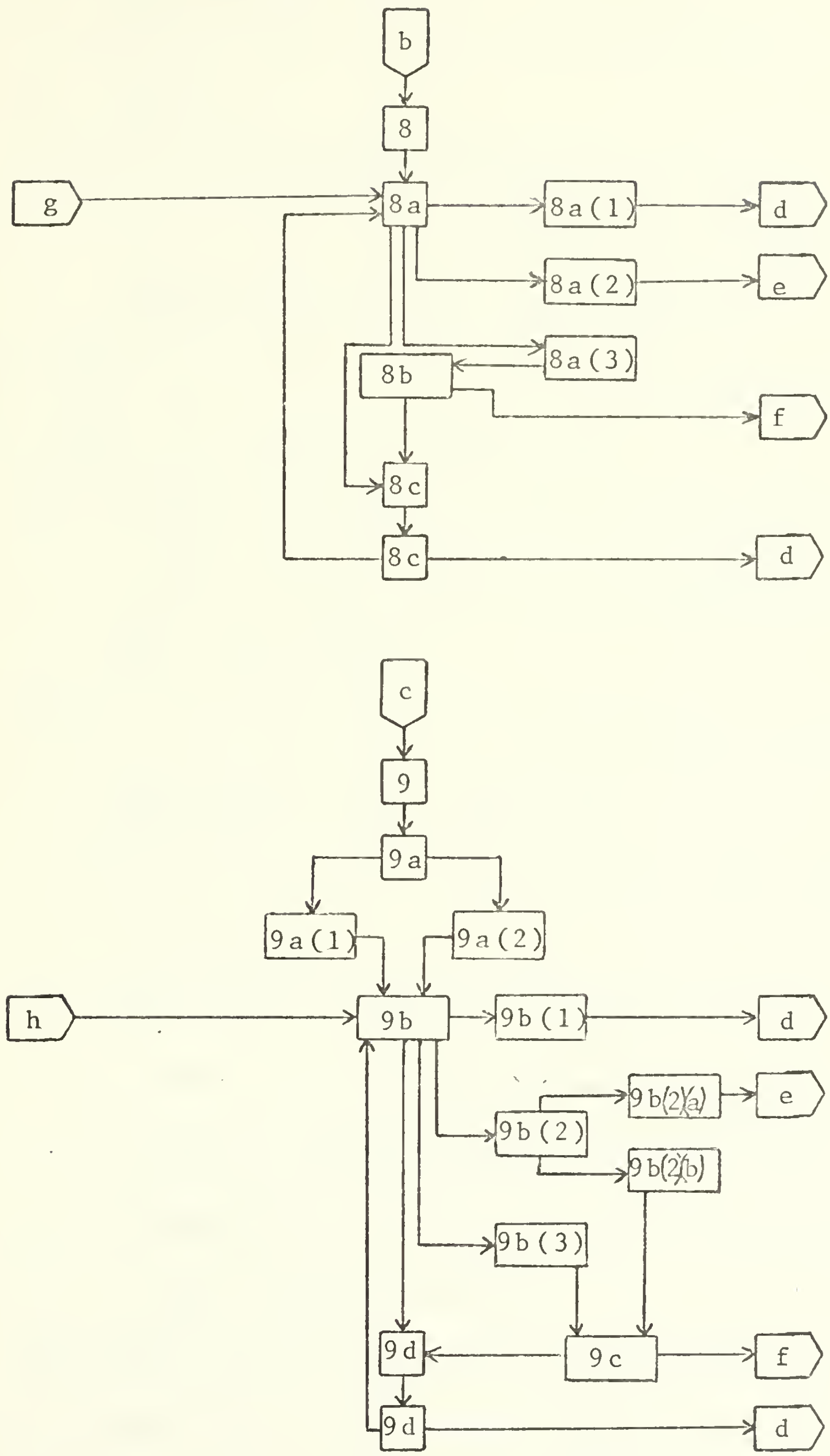
      (2) If either the NB vessel at PM or the next available SB vessel in Gatun Lake is a CC vessel, go to step 7.

      (3) If neither is a CC vessel, schedule the SB vessel through the Cut, when the Cut is clear of NB(CC) vessels, to the finish of transit. Schedule the NB vessel through the Cut when the Cut is clear of SB(CC) vessels, and through Gatun Lake. Continue to step 8b.

   b. If the scheduler desires to change lock lane loco capability at MF and PM locks, do so and go to step 6. Also, go to step 6 if a NB(6) vessel on the ready time list is available to start transit. Otherwise, continue to step 8c.

   c. If there is no NB(4) vessel remaining on the ready time list, go to step 11. Otherwise, schedule the next available NB(4) vessel through MF and PM locks in either lane, whichever is available without interfering with SB vessels, with priority given to the four-loco lanes. Return to step 8a.

Figure 3. Algorithm Flow Chart, Part B



9. a. (1) If the SB vessel(s) in PM lock are four-loco vessel(s), schedule them through to the finish of transit. Go to step 9b.

(2) If the SB vessel(s) in PM lock are six-loco vessel(s), remove them from PM lock and the Cut. Delay these vessel(s) in Gatun Lake. Go to step 9b.

b. If there is not a NB vessel at PM lock, go to step 9d. If there is a NB vessel at PM lock and:

(1) If there is no SB vessel available in Gatun Lake, schedule the NB vessel at PM lock through Gatun Lake. Go to step 11.

(2) If the next SB vessel in the order of finish transit of Gatun Lake is a SB(4) vessel and:

(a) If either this SB or the NB at PM is a CC vessel, go to step 7.

(b) If neither this SB or the NB vessel at PM is a CC vessel, schedule the SB vessel through the Cut, when the Cut is available, and then to the finish of transit. Schedule the NB vessel through the Cut and Gatun Lake. Continue to step 9c.

(3) If the next SB vessel in the order of finish of transit of Gatun Lake is a SB(6) vessel, delay this vessel in Gatun Lake and schedule the NB vessel through the Cut and Gatun Lake. Continue to step 9c.

c. If the scheduler desires to change lock lane loco capability at MF and PM locks, do so and go to step 6. Also go to step 6 if no NB(6) vessel on the ready time list is available to start transit. Otherwise, continue to step 9d.

d. If there is no NB vessel remaining on the ready time list, go to step 11. Otherwise, schedule the next available NB vessel on the ready time list through MF and PM locks in either lane, whichever is available without interfering with SB vessels, with priority given to the six-loco lanes. Return to step 9b.

10. If SB vessel(s) at PM lock have not yet been scheduled through the finish of transit, do so. Determine the status of NB vessels at PM lock and the next available SB vessel in Gatun Lake.

a. If there is not a NB vessel at PM lock, go to step 10c. If there is a NB vessel at PM lock and:

(1) If there is no SB vessel available in Gatun Lake, schedule the NB vessel at PM lock through Gatun Lake. Go to step 11.

(2) If either the NB vessel at PM or the next available SB vessel in Gatun Lake is a CC vessel, go to step 7.

(3) If neither is a CC vessel, schedule the SB vessel through the Cut, when the Cut is clear of NB(CC) vessels, to the finish of transit. Schedule the NB vessel through the Cut, when the Cut is clear of SB(CC) vessels, and through Gatun Lake. Continue to step 10b.

b. If the scheduler desires to change lock lane loco capability at PM and MF locks, do so and go to step 6; otherwise, continue to step 10c.

c. If there is no NB vessel remaining on the ready time list, go to step 11. Otherwise, schedule the next available NB vessel through MF and PM locks in either lane, whichever is available without interfering with SB vessels, with priority given to the lane assigned to NB vessels. Return to step 10a.

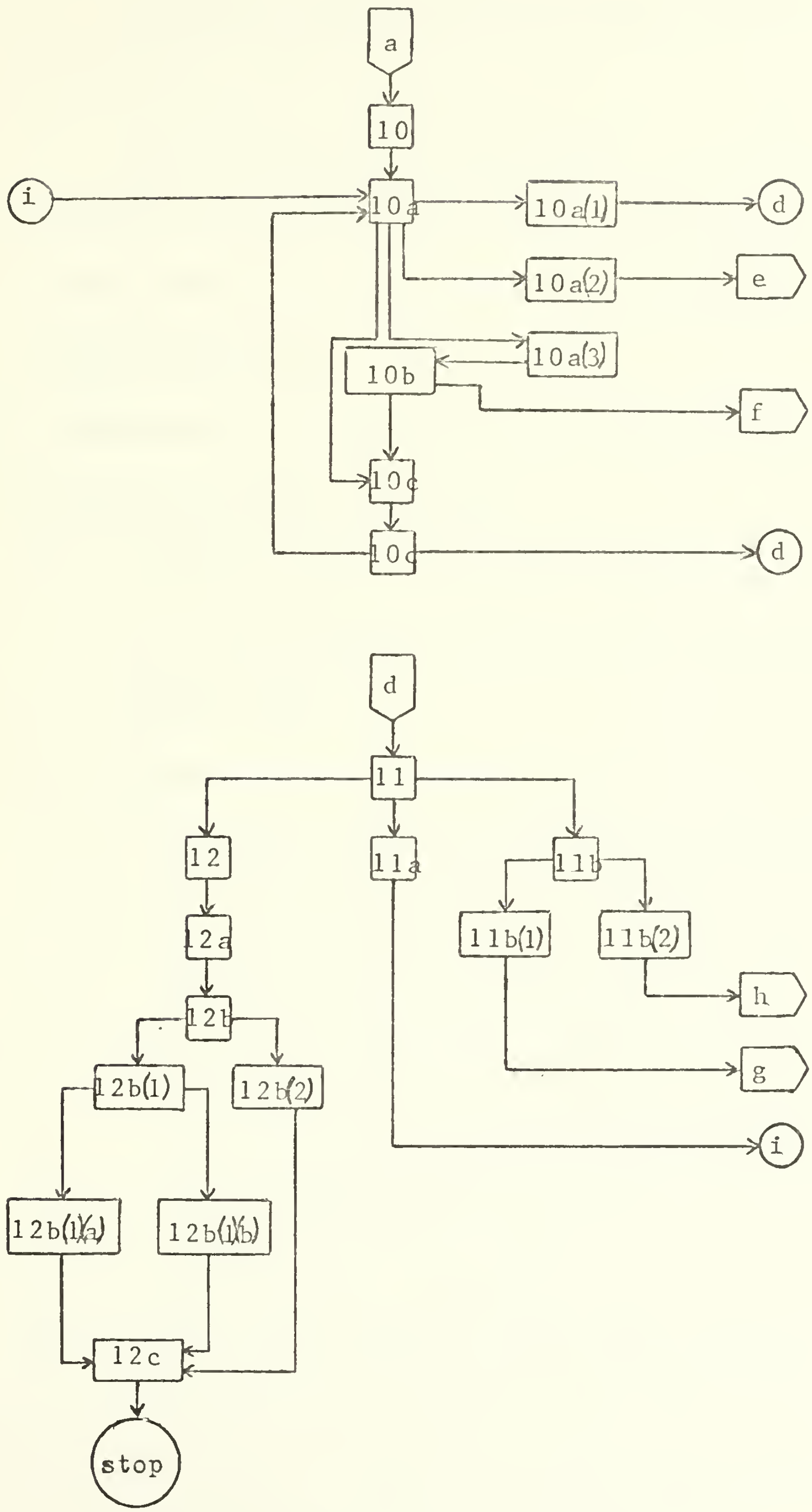
11. Assign lanes at Gatun lock based on loco requirements of vessels in each direction available for lockage. Switch lanes as necessary to allow SB vessels to transit Gatun lock without delay due to loco requirements. NB vessels take delays in Gatun Lake while awaiting an available lane. Schedule available NB and SB vessels through Gatun lock. Schedule NB vessels through to the finish of transit and SB vessels through Gatun Lake. Stop scheduling vessels through Gatun lock when there are no more SB vessels on the ready time list or when the last available NB vessel in Gatun Lake has been scheduled through Gatun lock to the finish of transit, then if there are no more NB vessels on the ready time list, go to step 12. Otherwise, if:

a. MF and PM locks are 6/6, go to step 10a.

b. MF and PM locks are 6/4, and:

(1) There are no more NB(6) vessels remaining on the ready

Figure 4. Algorithm Flow Chart, Part C



time list or NB(6) vessels remain on the ready time list but are not available to start transit, go to step 8a.

(2) There are NB(6) vessels remaining on the ready time list and available to start transit, go to step 9b.

12. a. Schedule any remaining NB vessels in Gatun Lake through Gatun lock to the finish of transit using DB operation. Continue to step 12b.

b. Schedule any remaining SB vessels in Gatun Lake through the finish of transit as follows:

(1) If all SB vessels in Gatun Lake completed transit of the lake with an interval of 40 minutes or greater between vessels, and:

(a) None of the vessels is a six-loco vessel, secure the six-loco lanes at PM and MF locks and schedule the SB vessels through the four-loco lanes to the finish of transit. Go to step 12c.

(b) Any of the vessels is a six-loco vessel, secure the four-loco lanes at PM and MF locks and schedule the SB vessels through the six-loco lanes to the finish of transit. Go to step 12c.

(2) If any of the SB vessels in Gatun Lake completed transit of the lake with an interval of less than 40 minutes between vessels; schedule the vessels through both lanes at MF and PM to the finish of transit until:

(a) The remaining vessels in the lake have a 40 minute or greater interval between vessels. Go to step 12b(1).

(b) No SB vessels remain in the lake. Go to step 12c.

c. All vessels have completed transit of the canal. Stop.

IV. VALIDATION OF THE SCHEDULING ALGORITHM

A. ACTUAL TRANSIT SCHEDULE

1. Analysis of Transit Data

In order to measure the effectiveness of schedules created by use of the scheduling algorithm, a comparison between an algorithm-created schedule, called the derived schedule, and an actual schedule, utilized for transiting vessels through the canal, was made. In order to make the comparison using a meaningful mix of vessels, transit data from available Transit Operations Sheets (TOS) were analyzed.

The data recorded on the TOS are the actual times of vessel transits and, therefore, should provide an accurate reflection of MTC scheduling practices and categories of vessels utilizing the canal. Only the first 15 of the 31 available Transit Operations Sheets for January, 1972, were utilized because reduction of canal capability due to lane outages during the latter half of the month was considered to provide an inaccurate reflection of scheduling practices and vessel categories.

The 24-hour statistics for the data utilized are presented below:

TABLE III. ANALYSIS OF TRANSIT DATA

Northbound Vessels (NB)	Mean	Standard Deviation
Vessels in 24 hours	14.20	3.33
Six-loco vessels	3.74	1.66
CC vessels	.80	.73
DL vessels	1.87	1.02
Southbound Vessels (SB)		
Vessels in 24 hours	14.30	2.17
Six-loco vessels	4.50	1.78
CC vessels	1.30	1.10
DL vessels	2.94	1.29

2. Choice of Actual Transit Schedule

Upon completion of the data analysis, the available TOS were searched in order to pick an actual transit schedule which would reflect at least average traffic demand or greater in all four categories described in table III. The TOS for 13 January, 1972, was picked as being most nearly fitted to the requirements specified.

Appendix D presents the actual schedule appearing on the TOS for 13 January, 1972. The scheduling form shown was designed for use in this report and does not represent the Panama Canal Company forms. Transit times appear on this schedule as elapsed times with midnight appearing as zero time in order to allow easier comparison with the derived transit schedule. MTCS use clock times when scheduling vessels through the canal. The data presented were modified slightly to conform to the assumptions stated in Section III of this paper. Tandem lockages are not considered which necessitated the elimination of two NB and three SB tandem pairs from the TOS. Only one ship of each tandem pair was retained in the data presented.

Only vessels in each direction which had completed lockage at the final set of locks by 2400 were considered. This requirement reduced the number of vessels considered for transit from 21 to 16 in the NB direction and from 18 to 15 in the SB direction.

As can be seen from the TOS represented in Appendix D, the following number of vessels in each of the above mentioned classifications transited the canal within the 24-hour scheduling period.

TABLE IV. ACTUAL VESSEL TRANSITS

	NB	SB
Vessels in 24 hours	16	15
Six-loco vessels	2	5
CC vessels	2	2
DL vessels	4	3

B. DERIVED SCHEDULE USING THE SCHEDULING ALGORITHM

1. Assumptions

Using the same mix of vessels shown in the TOS represented in Appendix D, the scheduling algorithm was employed to schedule the vessel transits of the canal. For the purposes of this example and to conform as nearly as possible to the schedule times for the actual transits of the daylight (DL) restricted vessels, daylight was assumed to begin at 0600 and end at 2000. Values of transit times through the various sections of the canal for each vessel and procedures for calculating Regular lockages were taken from Appendix B with three exceptions:

a. Individual vessel drafts were not available on the TOS used in the example. Gaillard Cut transit times were assumed to be 60 minutes for NB vessels and 65 minutes for SB vessels.

b. Individual vessel speed capabilities were not available. All vessels were assumed to have a 10-knot capability and, therefore, could transit Gatun Lake in 120 minutes.

c. Individual vessel cargo status and drafts were not available. The 90-99 foot row in the table was used for vessels with 90-99 foot beams and the 100+(laden) row was used for vessels with 100 foot or greater beams.

All locks were assumed to have a (6/4) capability. This assumption was necessary since information available on the TOS for the actual schedule did not indicate maximum lock lane locomotive capability at any given time.

2. Vessel Designation System

Individual vessels are identified by two methods in the explanation of the use of the scheduling algorithm. The first is by the vessel's precedence in the order of ready times in each direction. For example, the first vessel ready to transit in the northbound direction will be designated as 1N. The distinction between the ready time designation for a vessel and the abbreviation for a particular vessel's locomotive requirement, such as NB(4), should be clear. The second method of designation is by a vessel's transit order in the derived schedule. For example, the first vessel ready to transit in the northbound direction is designated 1N, however, this vessel may not be the first northbound vessel scheduled to transit. If 1N is, in fact, the fifth vessel scheduled to transit, the vessel will be assigned an additional designation as 1N5. A vessel will always have a ready time designation, but will not receive a transit order designation until it has actually been placed on the schedule. Finally, once a vessel has been placed on the schedule, the ready time designation may be dropped for easier reference and the vessel may be referred to by its direction and transit order (i.e., N5).

3. Use of the Scheduling Form

The scheduling form shown in Appendix D embodies most of the

information contained on the Panama Canal Company Transit Operations Sheet with some modification to facilitate the use of the scheduling algorithm. The form can be used for both northbound or southbound vessels and, when scheduling, one form is used for each direction. Northbound vessels are scheduled from left to right and southbound vessels from right to left.

The Ready Time Order (R.T. ORD.) column is filled in as vessels are scheduled to facilitate cross reference to the list of vessels in their order of ready times in step one of the algorithm. The Transit Order (TR. ORD.) is already filled in since vessels are scheduled from top to bottom on the form.

The remarks column is available for showing any special restrictions of the vessel being scheduled, such as a Clearcut or Daylight designation or special cargo being carried.

A vessel's beam width is entered in the appropriate column for use with Appendix B in determining the vessel's transit times through various sections of the canal.

Vessel locomotive requirements are entered in the designated column to facilitate scheduling of vessels through the appropriate lane at each set of locks.

Both east and west lock lanes at each set of locks have a space for designating the lane's locomotive capability in accordance with step one of the algorithm.

The Ready Time (R.T.) column is used to fill in the time the vessel was actually ready to commence transit. This time is used to compute Canal Zone Waters Time.

Once the schedule has been completed, each vessel's Intransit Time (I.T.Time) and Canal Zone Waters Time (C.Z.W.Time) is computed for statistical purposes and placed in the last two columns of the form.

The body of the Scheduling Form is used for recording the transit times through the various sections of the canal for each vessel being scheduled. For ease in scheduling, elapsed times in minutes are used with zero time as 0000 clock time and 1440 minutes as 2400 clock time. Vessel arrival and departure times through each section of the canal are entered in the appropriate space on the scheduling form as determined by the transit times for the vessel being scheduled which are contained in Appendix B. Any delays to the vessel in a specific section of the canal are indicated by a small oval, containing the value of the delay, drawn above the vessel's transit time through that section of the canal.

4. Derived Schedule

The same mix of vessels shown on the actual schedule, as regards the vessel classifications discussed in section IV-A-2, were used in illustrating and validating the scheduling algorithm. All times used in illustrating the algorithm are elapsed times with time zero as 2400 clock time.

Step one of the algorithm requires a listing of vessels to be scheduled in the order of their ready times along with other pertinent

information. This listing is illustrated in Table XVI in Appendix E. The notation in the remarks column of the table indicates that MF lock is available to transit vessels at time zero in the east lane and time 180 in the west lane. Both lanes at Gatun lock are available to transit vessels at time 180. This information was obtained from the previous day's TOS. In actual practice it would be taken from the previous day's schedule.

Lock lane loco capability is indicated in the appropriate spaces on the NB and SB scheduling forms illustrated in Tables XVII and XVIII in Appendix E. All locks are assumed to have (6/4) capability and by inspection of the previous day's schedule the earliest lanes available in each lock would be designated as six-loco lanes by the algorithm.

In step two the first available SB vessel in the ready time list is scheduled through Gatun lock, Gatun Lake, the Cut and PM lock. It is 4S since the previous vessels on the ready time list are all DL's. This vessel is scheduled to arrive at Gatun lock at time 180 to transit either lane since both are available at this time and 4S is a four-loco vessel. The vessel's transit times through each section of the canal are computed using the vessel's beam width and Table X in Appendix B.

Available NB vessels are next scheduled, using step 3b, through MF and PM locks, the Cut and Gatun Lake using the six-loco lanes since these lanes were the earliest lanes available at each lock. Vessel 1N is not available for transit since it is a DL. Vessel 2N is scheduled through MF lock starting at time zero, the earliest time this lock is available; 3N, 4N and 5N follow. At time 180 step 3c is used since both lanes at

MF and PM are now available. Vessel 6N is scheduled through the four-loco lanes since it is a four-loco vessel. Vessel 7N is not available for transit since it is a DL vessel. Vessel 8N is scheduled following 6N. Vessel 9N is not available since it is a DL. Vessel 10N is scheduled following 8N. Although 10N overlaps the time interval of 1S in the Cut there is no Cut conflict since neither vessel is a CC vessel. The next vessel available to start transit is 1N since 11N is not ready to start transit until time 300 and daylight occurs at time 360. 1N would then be able to start transit earlier than 11N to arrive at MF lock to begin lockage at time 360. Although 1N is a four-loco vessel it is scheduled through the six-loco lanes at MF and PM since they are next available. In accordance with step 3d, scheduling of NB vessels stops with 1N at PM lock since the time intervals of 1N and 4S overlap at PM. It should be noted that there is no actual conflict between these two vessels since the lock loco capability can handle both vessels in opposite lanes simultaneously.

At this time seven NB vessels have transited the Cut and are in Gatun Lake awaiting transit of Gatun lock. Using step 4c, since both lanes at Gatun lock are available at time 180, SB vessels are scheduled through both lanes and through Gatun Lake. Vessel 4S has already been scheduled through the six-loco lane although the choice was arbitrary. Vessel 5S is the next vessel available and it is scheduled through the four-loco lane. Vessel 6S is then scheduled through the six-loco lane. The first NB vessel, 2N1, is available to lock at Gatun at time 275 and double barreling of SB vessels is stopped using step 4d. If another SB

vessel had been scheduled through the next available lane N1 would have had to be delayed unnecessarily in Gatun Lake.

Using step 5, SB and NB vessels are scheduled through Gatun lock in appropriate lanes until there are no more NB vessels remaining in Gatun Lake for transit. After 7S transits Gatun lock DL vessels are eligible to start transit. Vessels 1S, 2S and 3S follow 7S through the six-loco lane. Ready time order is then resumed with 8S and 9S transiting the lock. Vessel 9S is the last SB vessel to transit the lock since the last NB vessel passed through the lock at time 720.

Step 6 resolves the "initial PM conflict" between 4S and 1N by assigning lock lanes based on NB vessel requirements and directing the scheduler to the next step. Step 6b(2) is used since 9N is available to start transit and is a six-loco vessel. The four-loco lanes are assigned to SB vessels and S1 is placed in the four-loco lane at PM. Since there is no "Cut conflict" at this time the scheduler is directed to step 9.

Using step 9a(1), S1 is scheduled through to the finish of transit. Vessel N8 is presently in PM lock and the next available SB vessel in Gatun Lake is S2 which is a four-loco vessel. Since N8 is a CC vessel, step 9b(2)(a) directs the scheduler to step 7. Vessel 9N is a CC vessel and S2 is not. Using step 7a(1), vessel N8 is delayed at PM for a total of 105 minutes (up to time 550) while awaiting N9 to transit MF and PM locks. During this delay S2 and S3 are scheduled through the Cut, PM and MF locks to the finish of transit since they are both four-loco vessels and the four-loco lanes were assigned to SB vessels. Vessel S4 was

not scheduled through the Cut since the Cut transit time of 65 minutes for SB vessels would have caused a delay to N8 (S4 would have started Cut transit at time 495. This time plus 65 minutes would have caused a 10 minute delay to N8 since N8 should start transit of the Cut at time 550). Both S2 and S3 are each delayed prior to transit of PM by tie-up along the approach wall while awaiting the lane to become available. After transit of the Cut by S2 and S3, N8 and N9 transit the Cut and Gatun Lake.

Using step 11, N8 and N9 are scheduled through Gatun lock. N8 is available for transit at time 730 but the six-loco lane is not available until time 770 due to the transit of S9 through this lane. When this lane becomes available N8 and N9 are scheduled through Gatun lock. Vessels 10S, 11S, and 12S are also scheduled through the lock in the four-loco lane. Vessel 12S completes transit of the lock at time 915 and N9 completes transit of the lock at time 920. No more NB vessels are available to transit Gatun lock and scheduling of transits at this lock stops.

Since a NB(6) vessel, 7N, is available to start transit at MF lock, step 11b(2) directs the scheduler to step 9b. Scheduling continues in the same manner until all vessels on the ready time list in each direction have been scheduled through all sections of the canal.

C. COMPARISON OF DERIVED AND ACTUAL SCHEDULES

The two schedules are compared using the Marine Traffic Control Scheduling Objectives described in Section II of this report.

The first objective is to maintain the maximum lockage capacity in the lock of least capacity. In order to measure lockage capacity at a lock, the quantity lock dead time was used. Lock dead time is defined as the total number of minutes during the scheduling period in which no vessel was using the lock after the lock transit interval had elapsed. This time is measured as the sum of the elapsed times between the end of the lock transit interval of one vessel and the entrance into the lock lane of the next vessel in either direction. The following lock dead times were computed from both the actual and derived schedules:

TABLE V. LOCK DEAD TIMES

	MF	PM	Gatun	
Actual Schedule	620	1080	65	(mins.)
Derived Schedule	845	560	30	

Utilization of the "lock of least capacity", Gatun lock, was marginally better in the derived schedule. There appeared to be a trade-off in usage between MF and PM locks. However, since the usage of MF and PM locks is probably better represented combined, due to the fact that vessels must transit both locks in sequence, the derived schedule with a total dead time at these two locks of 1405 minutes is better than the actual schedule which has a total dead time of 1700 minutes. This difference is probably due to the fact that the algorithm scheduled vessels through these two locks earlier than in the actual schedule.

The second objective is to obtain the lowest possible Intransit time and Canal Zone Waters time for each vessel. Intransit times and Canal Zone Waters times for each vessel are shown on the scheduling forms in Appendices D and E. The following statistics were computed for NB and SB vessels from the derived and actual schedules:

TABLE VI. CZW AND INTRANSIT TIMES

		CZW Time(min.)		Intransit Time(min.)	
		Avg.	S.D.	Avg.	S.D.
Actual Schedule	NB	884	237	420	48.5
	SB	914	393	387	51.2
Derived Schedule	NB	811	229	443	60.6
	SB	966	321	382	59.2

An apparent trade-off was made between NB and SB average CZW times in the actual and derived schedules. Standard deviations seem to favor the derived schedule slightly if decreasing NB average CZW time at the expense of increasing SB average CZW time can be accepted.

The opposite effect is observed on the comparison of Intransit times which seems to favor the actual schedule for the same reason discussed above.

Although conclusions on such a sparse data base are to be avoided, the results seem to indicate that the algorithm favors a reduction in NB CZW times and a general reduction in CZW time standard deviations in both directions at the expense of a slight increase in SB CZW times and Intransit times in both directions.

The total delay time while intransit for vessels in each direction was also computed. In the derived schedule total vessel delays in each direction were easily computed since delays are indicated explicitly on the scheduling form. Vessel delays were not indicated on the TOS. Using vessel beam width, each vessel's Intransit time through the canal with no delays was determined using Table X in Appendix B. This value of Intransit time for each vessel was then subtracted from the actual Intransit times for each vessel obtained from the TOS. The difference was assumed to be each vessel's delay while intransit. Total delays to vessels in each direction while intransit are presented in Table VII.

TABLE VII. DELAY TIMES

		Total Delay Time	
Actual Schedule	NB	1320	(mins.)
	SB	645	
Derived Schedule	NB	1655	
	SB	515	

The actual schedule is obviously superior in regard to total vessel delays. This data also correlates well with that presented in Tables V and VI. Intransit times for vessels in the NB direction are slightly higher in the derived schedule indicating larger delays and Intransit times for vessels in the SB direction are slightly lower in the derived schedule indicating smaller delays. Lock dead times are also less in the derived schedule which seems to indicate that vessels delayed within the canal are more readily available for lockage when a lock becomes available.

The third objective is to maintain a reasonable balance between NB and SB shipping. The same number of vessels were transited in both schedules, although in the derived schedule the last SB finished later and the last NB finished earlier than in the actual schedule. This could have been resolved by delaying a NB longer in the lake and allowing a SB vessel to transit Gatun lock in its place. This would have had the effect of adding about 60 minutes to the last NB vessel's finish time and subtracting about 60 minutes from the last SB vessel's finish time.

The last objective is to reduce overtime at the locks as much as possible. A study of the actual and derived schedules shows that one lane at each lock could be secured at the following clock times without affecting subsequent scheduling:

TABLE VIII. LOCK SECURING TIMES

	Lock		
	MF	PM	Gatun
Actual Schedule	2140	1940	2305
Derived Schedule	1735	1640	2005

The results in Table VIII using the scheduling algorithm appear markedly better than present scheduling procedures. The reason for this seems to be the algorithm's practice of starting vessel transits earlier and letting vessels take delays in Gatun Lake during transit vice at anchorage prior to transit. This practice decreases dead time at the locks, as indicated in Table V, thereby allowing the securing of one lock lane at each lock much sooner.

Because some of the assumptions made in the derivation of the scheduling algorithm affect the comparison between derived and actual schedules it is appropriate to discuss them briefly. The TOS utilized in the make-up of the actual schedule did not indicate lock locomotive capability and a (6/4) capability was therefore assumed at all locks. A study of the actual schedule indicates the certainty of a (6/6) capability at Gatun and possibly at PM and MF (unless locomotive crew lane switching occurred). In addition, Relay lockage procedures were evidently used at MF locks although this is also not indicated explicitly on the TOS.

Vessel tug requirements and availability of tugs were not accounted for although tugs were definitely required for certain vessels.

Tandem pairs were used in the unmodified actual schedule which means that more vessels (two NB and three SB) actually transited the canal in the 24-hour time span than did in the derived schedule. However, a study of the actual schedule shows that some vessels transited various sections of the canal in a shorter time period than the transit time table in Appendix B would indicate. Thus, the derived schedule, using transit times from Appendix B, was a very conservative schedule allowing more time than necessary for transit. The fact must be borne in mind that the TOS (from which the actual schedule was derived) shows the actual times of completed transits while the derived schedule is only a schedule, using the transit time table available.

Since vessel speed capability was not indicated on the TOS, transit times through Gatun Lake were computed on the basis of a ten-knot

capability giving a 120 minute transit time. Vessel draft and cargo status was also not available and transit time assumptions for all vessels in the Cut and for vessels with greater than 90 foot beam widths were made as indicated earlier in this section of the report.

In summary, the performance of the scheduling algorithm compared quite favorably to current scheduling practices for the particular mix of vessels considered.

None of the assumptions made in the derivation of the algorithm were considered to have been detrimental to the comparison of the two schedules except the assumption of a 6/4 lock locomotive capability when the locks probably had a 6/6 capability. This would tend to falsely favor the actual schedule results over the results obtained using the algorithm.

In the case tested the algorithm fulfilled all MTC scheduling objectives at least as well as the present scheduling practices with exception of obtaining the lowest possible Intransit and CZW times for the particular mix of vessels. However, based on the results of the comparisons between the other measures of effectiveness it would appear that more study of the interactions between these measures is necessary. For instance, the effect of higher vessel intransit delays for the SB vessels may have the effect of reducing CZW times for these vessels as it did for NB vessels. This, however, also has the effect of increasing vessel Intransit times as it did for NB vessels. Reduced CZW times would be considered good for vessel owners as it frees the vessels for revenue producing and reduced Intransit times are considered better for canal operations.

V. CONCLUSIONS

A. SUMMARY

The scheduling algorithm appears to compare favorably with present scheduling practices although additional testing with other vessel mixes needs to be undertaken. In addition, the measures of effectiveness developed for use in this paper are considered to be valuable tools, not only in comparing schedules, but also in developing and testing new scheduling techniques. These measures of effectiveness seem to correlate very favorably with one another and future study of their interactions is recommended. In this regard, the scheduling algorithm seems to have been effective in reducing CZW times for vessels by increasing intransit delays, and therefore, increasing Intransit times. There appears to be a trade-off between shorter CZW times at the expense of longer Intransit times which could be significant in making scheduling decisions.

The algorithm is considered to be valuable in the way that it approaches the scheduling problem. It helps in avoiding a great many false starts by proceeding in a logical manner with the arrangement of vessels for transit and through the actual scheduling process. This approach could be an excellent training aid for apprentice schedulers and will also provide an excellent base for developing a computer scheduling technique for vessel transits.

B. MODIFICATIONS NEEDED FOR ACTUAL USE

In order to effectively use the scheduling algorithm in normal canal operations there are several requirements which must be incorporated into it. Procedures must be included for handling eight locomotive vessels and eight locomotive lock capability, clear channel vessels, vessel tug requirements, vessel tandem pairs, locomotive crew switching between lock lanes, the incorporation of the 170 foot beam rule in the Cut and Relay lockages.

Incorporating decision rules within the algorithm for handling eight locomotive requirements and Relay lockages are straightforward and would require only minimal effort as would the inclusion of the beam rule.

Tandem lockages could also be incorporated if a sound decision rule could be formulated as to which vessels should be combined. In actual operation of the algorithm tandem pairs would be handled as single vessels but with increased locomotive requirements.

Procedures for handling clear channel vessels, tug requirements and lock lane crew switching would be much more difficult to incorporate as they involve developing a new set of decision rules for establishing priorities among transiting vessels.

C. SUGGESTIONS FOR IMPROVING THE DATA BASE

Many discrepancies were found between the transit times given in the Table of Transit Times, Appendix B, for scheduling vessels through the canal and the Transit Operations Sheet used in recording the actual transits. It is

recommended that the Table of Transit Times be modified to reflect actual vessel transit capabilities in order to provide more accurate scheduling information.

The Transit Operations Sheets were also found lacking in information with which to form an adequate statistical base for many types of research. The Transit Operations Sheets should be modified to provide an area to adequately indicate vessel cargo status, vessel draft and lock locomotive capability. If lock culvert status during each vessel's transit is not available in other records, it should be included on the TOS so that accurate lock transit times may be established. In this regard, vessel delays while in-transit should also be explicitly indicated on the TOS to assist in the compilation of statistics.

APPENDIX A

VESSEL RESTRICTIONS AND REQUIREMENTS

TABLE IX. TABLE OF VESSEL RESTRICTIONS AND REQUIREMENTS[7]

			RESTRICTIONS						REQUIREMENTS			
							TANDEM WITH HANDLINE LIMIT 750'		TUGS			
			CLEAR CHANNEL	DAYLIGHT TRANSIT	DAYLIGHT IN CUT	CLEARCUT	TANDEM TOTAL LIMIT 800'	HANDLINE TOTAL LIMIT 800'	LOCKS IN	LOCKS OUT	CUT 18	LOCOMOTIVES & WIRES
LENGTH OVER 800'	LENGTH OVER	675' BRIDGE AFT	A, B, C				NO	YES[1]				6/12
LENGTH OVER 600'	BEAM	100' AND OVER	A, B, C & D	YES	YES	YES	NO	YES[1]	2	1	1	6/12
		95' TO 99.5'	E	YES	YES	YES	NO	YES[1]	2	1[3]	1	6/12
		91' TO 94.9'	E	YES	YES	YES[12]	NO	YES[1]	2	0	1	6/12
		85.1' TO 90.9'	NO	YES[4]	YES[5]	NO	NO	YES[1]	1[3]	0	0[6]	6/12
		80' TO 85'	NO	NO	NO[5]	NO	NO	YES[1]	1	0	0[6]	6/12
		75' TO 79.9'	NO	NO	NO	NO	NO	YES[1]	1[7]	0	0	6/12
		UNDER 74.9'	NO	NO	NO	NO	NO	YES[1]	0[6]	0	0	6/12
LENGTH UNDER 600'	BEAM	85.1' TO 90.9'	NO	YES[4]	YES[5]	NO	YES	YES	1[3]	0	0[6]	4/6[14]
		80' TO 85'	NO	NO	NO[5]	NO	YES	YES	1[15]	0	0[6]	4/6[14]
		75' TO 79.9'	NO	NO	NO	NO	YES	YES	1[7]	0	0	4/6[14]
		UNDER 74.9'	NO	NO	NO	NO	YES	YES	0	0	0	4/6[14]
		450' TO 500'	NO	NO	NO	NO	YES	YES	0	0	0	4/4[13]
	CARGO	EXPLOSIVES XHEXP-A	NO	YES[11]	YES[11]	YES[17]	NO[16]	YES	0	0	0	
		PROPANE CLASSES 1 & 2	NO	NO	NO	YES	NO	YES[8]	0	0	0	
		GASOLINE NAPHTHA XHB OR XHC	NO	NO	NO	NO	YES[10]	YES[8]	0	0	0	

A. Gatun Locks to buoys 13 & 14
B. Balboa basin to buoys 13 & 14
C. If maximum draft over 38' Miraflores Locks to buoys 1 & 2
D. Miraflores Locks or from docks to buoys 1 & 2 at night
E. Balboa basin to Thatcher Ferry Bridge

1. Company craft not to exceed 850' total length
2. On request when laden
3. 2 tugs into Pedro Miguel southbound if beam over 87'
4. Yes: If Gatun Lake level over 84' and mean draft over 34'
   If Gatun Lake level under 84' and mean draft over 33'
   If Gatun Lake level under 83' and mean draft over 32'
5. Yes, if mean draft over 36'
6. No, if draft not over 30' and drag is not over 6'
7. Tug on pilot's request
8. Unless authorized for specific ships
9. 350' length limit on vessel with locomotives
10. 650' limit overall with small tankers (GULF KEY and SEATOWN type)
11. No, if waived by Port Captain
12. No, if combined beams do not exceed 170' and cargo is not grade "A" liquid or class 1 & 2 liquified flammable gases
13. 6 wires at pilot's option
14. Length 500.1' to 570' - 4 locomotives 6 wires unless vessel displaces over 25,000 tons, then, 4 locomotives 8 wires
    Length 570.1' to 600' - 4 locomotives 8 wires unless vessel displaces over 30,000 tons, then, 6 locomotives 10 wires, or at pilot's request, 12 wires.
15. Vessel with bow thrusters-tug on request
16. Yes, if XHEXP-B or XHEXP-C
17. If 5 tons or less, may be waived
18. If vessel displaces over 50,000 tons, then, 2 tugs in all locks and one in Gaillard Cut.

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7 Marine Traffic Control Manual, Panama Canal Company, p70.

APPENDIX A

VESSEL RESTRICTIONS AND REQUIREMENTS

TABLE IX. TABLE OF VESSEL RESTRICTIONS AND REQUIREMENTS[7]

		RESTRICTIONS				TANDEM WITH HANDLINE LIMIT 750		REQUIREMENTS			
		CLEAR CHANNEL *	DAYLIGHT TRANSIT	DAYLIGHT IN CUT	CLEARCUT	TANDEM TOTAL LIMIT 800'	HANDLINE TOTAL LIMIT 800'	TUGS LOCKS IN	TUGS LOCKS OUT	TUGS CUT 18	LOCOMOTIVES & WIRES
LENGTH OVER	675' BRIDGE AFT	A, B, C				NO	YES [1]				6/12
LENGTH OVER 800' — BEAM	100' AND OVER	A, B, C & D	YES	YES	YES	NO	YES [1]	2	1	1	6/12
LENGTH OVER 800' — BEAM	95' TO 99.9'	E	YES	YES	YES	NO	YES [1]	2	1 [2]	1	6/12
LENGTH OVER 800' — BEAM	91' TO 94.9'	E	YES	YES	YES [12]	NO	YES [1]	2	0	1	6/12
LENGTH OVER 800' — BEAM	85.1' TO 90.9'	NO	YES [4]	YES [5]	NO	NO	YES [1]	1 [3]	0	0 [4]	6/12
LENGTH OVER 800' — BEAM	80' TO 85'	NO	NO	NO [5]	NO	NO	YES [1]	1	0	0 [4]	6/12
LENGTH OVER 800' — BEAM	75' TO 79.9'	NO	NO	NO	NO	NO	YES [1]	1 [7]	0	0	6/12
LENGTH OVER 800' — BEAM	UNDER 74.9'	NO	NO	NO	NO	NO	YES [1]	0 [8]	0	0	6/12
LENGTH UNDER 800' — BEAM	85.1' TO 90.9'	NO	YES [4]	YES [5]	NO	YES	YES	1 [3]	0	0 [4]	4/6 [14]
LENGTH UNDER 800' — BEAM	80' TO 85'	NO	NO	NO [5]	NO	YES	YES	1 [18]	0	0 [4]	4/6 [14]
LENGTH UNDER 800' — BEAM	75' TO 79.9'	NO	NO	NO	NO	YES	YES	1 [7]	0	0	4/6 [14]
LENGTH UNDER 800' — BEAM	UNDER 74.9'	NO	NO	NO	NO	YES	YES	0	0	0	4/6 [14]
LENGTH UNDER 800'	450' TO 500'	NO	NO	NO	NO	YES	YES	0	0	0	4/4 [13]
CARGO	EXPLOSIVES XHEXP-A	NO	YES [11]	YES [11]	YES [17]	NO [16]	YES	0	0	0	
CARGO	PROPANE CLASSES 1 & 2	NO	NO	NO	YES	NO	YES [8]	0	0	0	
CARGO	GASOLINE NAPHTHA XHB OR XHC	NO	NO	NO	NO	YES [10]	YES [9]	0	0	0	

A. Gatun Locks to buoys 13 & 14
B. Balboa basin to buoys 13 & 14
C. If maximum draft over 38' Miraflores Locks to buoys 1 & 2
D. Miraflores Locks or from docks to buoys 1 & 2 at night
E. Balboa basin to Thatcher Ferry Bridge

1. Company craft not to exceed 850' total length
2. On request when laden
3. 2 tugs into Pedro Miguel southbound if beam over 87'
4. Yes: If Gatun Lake level over 84' and mean draft over 34'
   If Gatun Lake level under 84' and mean draft over 33'
   If Gatun Lake level under 83' and mean draft over 32'
5. Yes, if mean draft over 36'
6. No, if draft not over 30' and drag is not over 6'
7. Tug on pilot's request
8. Unless authorized for specific ships
9. 350' length limit on vessel with locomotives
10. 650' limit overall with small tankers (GULF KEY and SEATOWN type)
11. No, if waived by Port Captain
12. No, if combined beams do not exceed 170' and cargo is not grade "A" liquid or class 1 & 2 liquified flammable gases
13. 6 wires at pilot's option
14. Length 500.1' to 570' - 4 locomotives 6 wires unless vessel displaces over 25,000 tons, then, 4 locomotives 8 wires
    Length 570.1' to 600' - 4 locomotives 8 wires unless vessel displaces over 30,000 tons, then, 6 locomotives 10 wires, or at pilot's request, 12 wires.
15. Vessel with bow thrusters-tug on request
16. Yes, if XHEXP-B or XHEXP-C
17. If 5 tons or less, may be waived
18. If vessel displaces over 50,000 tons, then, 2 tugs in all locks and one in Gaillard Cut.

[7]Marine Traffic Control Manual, Panama Canal Company, p70.

EN.IX A

NS AND REQUIREMENTS

IC IS AND REQUIREMENTS 7

HANDLINE TOTAL LIMIT 600'	REQUIREMENTS: TUGS, LOCKS IN	TUGS, LOCKS OUT	CUT 18	LOCOMOTIVES & WIRES
YES 1				
YES 1				
YES 1	2	1		
YES 1	2	1 3	1	6/12
ES 1	2	0	1	6/12
S 1	1 3	0	1	6/12
1	1	0	0 4	6/12
YE 1	1 1	0	0 4	6/12
YES	0 6	0	0	6/12
ES	1 2	0	0	6/12
S	1 10	0	0 4	6/12
	1 7	0	0 4	4/6 14
	0	0	0	4/6 14
	0	0	0	4/6 14
	0	0	0	4/6 14
		0	0	4/4 13
		0	0	
		0	0	

valved by Port Captain
ombined beams do not exceed 170' and
o is not grade "A" liquid or class
liquified flammable gases
pilot's option
.1' to 570' - 4 locomotives 6 wires
vessel displaces over 25,000 tons,
locomotives 8 wires
' to 600' - 4 locomotives 8 wires
ssel displaces over 30,000 tons,
comotives 10 wires, or at pilot's
2 wires.
thrusters-tug on request
or XHEXP-C
may be waived
es over 50,000 tons, then,
locks and one in Gaillard Cut.

ninutes more in the Cut than north-
slow down approaching Pedro Miguel

0 minutes longer from Cristobal to
nd vessels because moving out of the
nal time.
are contained in Table XI and depend on
ve requirement and draft.

TABLE X. CANAL TRANSIT TIMES

Vessel Size Beam in Feet	Balboa entrance to Basin[1]	Basin to Locks[1]	Miraflores Locks Transit	Miraflores Locks Interval regular	Miraflores Locks Interval relay Up	Miraflores Locks Interval relay Down	Miraflores Lake	Pedro Miguel Locks Transit	Pedro Miguel Locks Interval		Gatun Lake[3] Average speed knots	Gatun Lake[3] Gatun Lake time	Gatun Locks Transit	Gatun Locks Interval regular	Gatun Locks Interval relay	Gatun[4] Lock to Cristobal
50	30	30	35	40	30	30	20	25	35				50	1:00	30	30
50-59	30	30	40	45	30	30	20	25	35				50	1:00	30	
60-69	30	30	40	50	30	30	25	30	40				55	1:05	30	
70-79	30	30	45	55	35	35	25	30	40				1:00	1:10	35	
80-89	30	30	50	60	35	40	25	35	45				1:05	1:15	40	
Deeply Laden D 36	30	30	55	1:05	35	40	25	40	50				1:10	1:20	40	
90-99	30	30	1:00	1:10	40	45	25	40	50		15	1:30	1:10	1:20	40	35
90-99 Laden 36' D 30'	30	30	1:10	1:20	45	50	30	50	1:00		12	1:45	1:20	1:30	45	35
90-99 Deeply Laden 36	30	35	1:15	1:25	50	55	30	55	1:05		10	2:00	1:30	1:40	50	40
100+ Ballast	30	30	1:05	1:15	45	50	25	45	55		8	2:45	1:15	1:25	45	35
100+ Laden 36 D 30	30	30	1:15	1:25	50	55	30	55	1:05		6	3:45	1:30	1:40	55	35
100+ Deeply Laden 36	30	35	1:25	1:35	1:00	1:00	30	1:00	1:10		4	5:30	1:50	2:00	1:00	40
Tandem	30	30	50	1:00	40	40	20	35	45				1:05	1:15	40	35
			(+10 min. if S. W. culvert)[5]	(+10 if S.W. culvert both regular & relay)[5]				(+5 min. if S.W. culvert)[5]	(+10 if S.W. culvert)[5]				(+15 min. if S.W. culvert)[5]	(+15 min. if S.W. culvert)[5]	(+10 if S.W. culvert relay)[5]	

[1] Subtract 5 min. for southbounds.
[2] For southbounds add 5 min.
[3] Ships with length 600' or draft 38' average 10 knots.
[4] Add 30 min. for southbounds. Their time starts from the anchorage.
[5] If centerwall culvert only, double factor added for sidewall culvert only.

TABLE XI

GAILLARD CUT TRANSIT TIMES

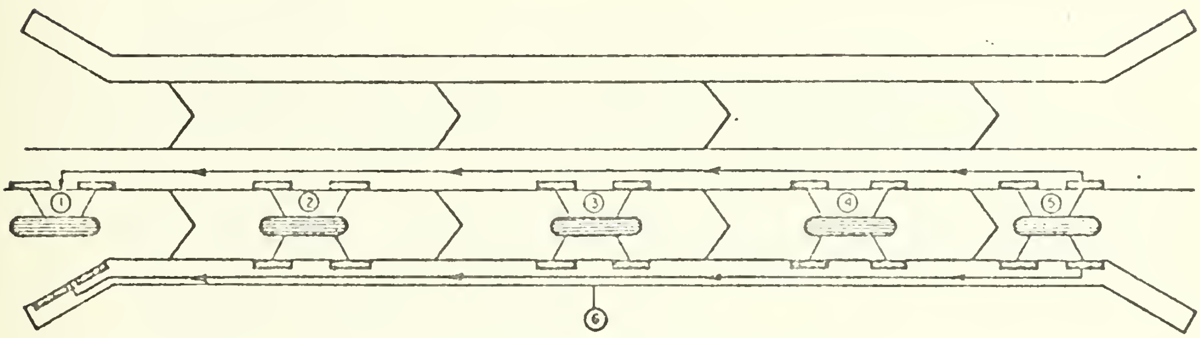
Northbound	(Hours:Minutes)
Any vessel in ballast	1:00
Any vessel with draft under 34 feet	1:00
Any vessel with draft 34 to 36 feet	1:05
Any vessel with draft 36 to 37 feet	1:10
Any vessel with draft 37 feet and over	1:15
Southbound	
4 locomotive vessel in ballast	1:00
4 locomotive vessel loaded	1:05
6 locomotive vessel in ballast	1:05
Draft not over 34 feet	1:10
Draft 34 to 36 feet	1:15
Draft 36 to 37 feet	1:20
Draft over 37 feet	1:25

APPENDIX C. LOCKAGE PROCEDURES

Figure 5. Diagram of Regular and Relay Lockage Procedure[9]

REGULAR LOCKAGES
GATUN LOCKS

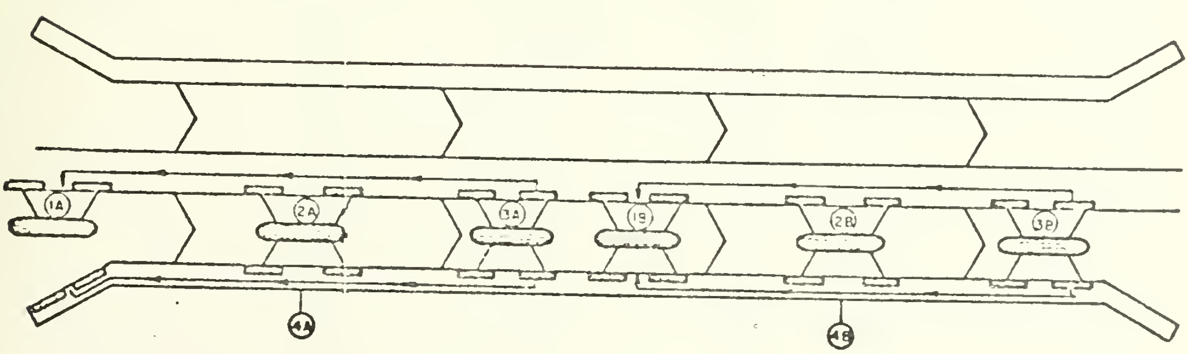
1 - LOCOMOTIVES SECURED SHIP AT TIE UP STATION
2 - SHIP MOVED INTO FIRST LEVEL
3 - SHIP MOVED INTO MIDDLE LEVEL
4 - SHIP MOVED INTO LAST LEVEL
5 - SHIP MOVED OUT OF LAST LEVEL
6 - LOCOMOTIVES OFF - RETURN TO TIE UP STATION TO SECURE NEXT SHIP



RELAY LOCKAGES
GATUN LOCKS

A FIRST SET OF LOCOMOTIVES
B SECOND SET OF LOCOMOTIVES

1A - LOCOMOTIVES SECURED SHIP AT TIE UP STATION
2A - SHIP MOVED INTO FIRST LEVEL
3A - SHIP MOVED INTO MIDDLE LEVEL
4A - LOCOMOTIVES OFF - RETURN TO TIE UP STATION TO SECURE NEXT SHIP
1B - LOCOMOTIVES RELAY AND SECOND SET OF LOCOMOTIVES READY TO MOVE SHIP INTO LAST LEVEL
2B - SHIP MOVED INTO LAST LEVEL
3B - SHIP MOVED OUT OF LAST LEVEL
4B - LOCOMOTIVES OFF - RETURNED TO MIDDLE LEVEL AND READY TO RELAY NEXT SHIP



[9] Marine Traffic Control Manual, Panama Canal Company, p83.

Example of Regular Lockage Timing[10]

1. All times are rounded to the next five minutes.
2. Arrival time between two consecutive vessels in the same direction is equal to the Regular lockage interval of the first vessel.
3. Arrival time between the last and first vessel during a change of direction is equal to the lock transit time of the last vessel plus ten minutes.
4. Clearance time is equal to arrival time plus transit time.
5. If only the sidewall culvert is used for filling or emptying the lock chamber, add to the transit or interval times the values indicated in Table X in Appendix B.
6. Lockage intervals and transit times for a given vessel's beam are given in Table X.

TABLE XII

REGULAR LOCKAGE TIMING AT MIRAFLORES LOCK

Beam	Vessel Transit Order No.	Regular Lockage Interval	Transit Time	Arrival	Clearance
53	N1	45 min.	40	0:00	0:40
73	N2	55	45	0:45	1:30
82 Ballast	N3	60	50	1:40	2:30
64	S1	50	40	2:40	3:20
90 ballast	S2	1:10	1:00	3:30	4:30

[10] Ibid., p. 79.

Example of Relay Lockage Timing[11]

1. All times are rounded to the next five minutes.
2. Lockage transit time for a Relay lockage is the same as for a Regular lockage minus the time to approach tie-up (T/U) station; that is, five minutes for tandems and vessels with beams less than 80' and ten minutes for all other vessels. Clearance time is equal to ready-to-enter time plus Relay lockage transit time.
3. Ready-to-enter time between two consecutive vessels in the same direction is equal to the Relay lockage interval of the first vessel.
4. Ready-to-enter time between the last and first vessel during a change of direction is equal to the clearing time of the last vessel plus ten minutes.
5. Arrival for tie-up time is equal to the ready-to-enter time of the previous vessel in the same direction.
6. If only the sidewall culvert is used for filling or emptying the lock chamber, add to the transit or interval times the values indicated in Table X in Appendix B.
7. Lockage intervals and transit times for a given vessel's beam are given in Table X.

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[11] Ibid., p. 80.

TABLE XIII

RELAY LOCKAGE TIMING AT MIRAFLORES LOCK

Beam	Vessel Transit Order No.	Relay Lockage Interval	Transit Time (Relay Lockage)	Arrival for T/U	Ready to Enter	Clearance
53	N1	30 min.	35		0:00	0:35
75	N2	35	40	0:00	0:30	1:10
82 Ballast	N3	35	40	0:30	1:05	1:45
64	S1	30	35		1:55	2:30
90 Ballast	S2	45	50	1:55	2:25	3:15

APPENDIX D. ACTUAL TRANSIT SCHEDULE

TABLE XIV. MODIFIED ACTUAL SCHEDULE (NORTHBOUND)

NORTHBOUND/~~SOUTHBOUND~~ SCHEDULING FORM

R.T. ORD.	TR. ORD.	REMARKS	BEAM	LOCOS	PACIFIC CHANNEL	MF LOCK E( )	MF LOCK W( )	MF LAKE	PM LOCK E( )	PM LOCK W( )	CUT	GATUN LAKE	GATUN LOCK E( )	GATUN LOCK W( )	ATLANTIC CHANNEL	R.T.	I.T. TIME	CZW TIME
2	1		64	4	104-175		175-213	213-225	225-250		250-301	301-415		415-474	474-500	-455	300	755
3	2		56	4	126-184		184-243	243-258	258-283		283-335	335-484	484-544		544-565	-220	360	755
4	3		60	4	147-212		212-275	275-293	293-319		319-375	375-549		549-605	605-630	-105	390	790
5	4		71	4	177-247		247-315	315-330	330-355		355-414	414-619		619-670	670-695	-140	425	835
6	5		75	4	232-289		289-352	352-375	375-405		405-465	465-674		674-737	737-763	-100	450	865
1	6	CC/DL	27	4	295-345	345-382		382-427		427-456	456-555	555-722	722-770		770-810	-760	425	1565
9	7	CC/DL	105	6	325-407		407-456	456-483		483-519	519-582	582-696		696-810	810-850	70	400	780
7	8	DL	90	6	391-473		473-523	523-540		540-570	570-625	625-782		782-887	887-916	65	415	910
14	9		84	4	510-547		547-648	648-669		669-712	712-774	774-937	937-1004		1004-1031	480	410	550
12	10	DL	61	4	570-661		661-704	704-730		730-753	753-826	826-982		982-1038	1038-1054	305	390	755
8	11		56	4	656-714		714-756	756-768		768-793	793-850	850-1102	1102-1166		1166-1192	35	450	1160
10	12		61	4	697-765		765-806	806-820		820-846	846-900	900-1193		1193-1255	1255-1301	110	490	1200
15	13		51	4	765-819		819-861	861-890		890-917	917-975	975-1243	1243-1312		1312-1338	480	410	865
11	14		71	4	815-889		889-934	934-952	952-981		981-1038	1038-1323		1323-1375	1375-1315	300	435	1100
13	15		62	4	865-940		940-981	981-1001		1001-1027	1027-1090	1090-1325	1325-1385		1385-1409	550	445	1090
16	16		63	4	975-1032		1032-1071	1071-1084		1084-1180	1180-1222	1222-1381		1381-1440	1440-1465	535	410	900

TABLE XV. MODIFIED ACTUAL SCHEDULE (SOUTHBOUND)

~~NORTHBOUND~~/SOUTHBOUND SCHEDULING FORM																		
R.T. ORD.	TR. ORD.	REMARKS	BEAM	LOCOS	PACIFIC CHANNEL	MF LOCK		MF LAKE	PM LOCK		CUT	GATUN LAKE	GATUN LOCK		ATLANTIC CHANNEL	R.T.	I.T. TIME	CZW TIME
						E( )	W( )		E( )	W( )			E( )	W( )				
6	1		62	4	485-540	445-485		436-445	411-436		350-411	235-350	184-235		135-184	60	300	450
5	2		61	4	557-614	511-557		482-511	450-482		393-450	259-393		200-259	145-200	-60	355	610
4	3		60	4	586-672		544-586	521-544	491-521		424-491	310-424	256-310		200-256	180	330	850
9	4		62	4	608-651	566-608		556-566	505-556		432-505	335-432		281-335	235-281	120	325	560
8	5		72	4	721-778	676-721		664-676	636-664		584-636	374-584	323-374		273-323	90	395	690
7	6		80	6	769-830	723-769		704-723	671-704		597-671	401-597		336-401	280-336	60	430	770
3	7	CC/DL	101	6	870-925	799-870		771-799	715-771		637-715	474-637	388-474		332-388	-170	450	1110
1	8	DL	85	6	930-990	840-930		814-840	773-814		693-773	542-693		483-542	402-483	-840	445	1330
2	9	DL	88	6	983-1052	890-983		866-890	831-866		759-831	632-759	561-632		440-561	620	425	1075
12	10		64	4	1059-1115	1003-1059		940-1003		928-940	860-928	718-860	648-718		605-648	300	410	515
13	11		84	6	1133-1205	1092-1133		1065-1092	1025-1065		957-1025	850-957	788-850		730-788	615	340	530
10	12		64	4	1246-1303	1202-1246		1108-1202	1080-1108		1020-1080	930-1020	808-930		753-808	120	440	1150
14	13	CC	63	4	1300-1375	1223-1300		1172-1223	1165-1172		1095-1165	972-1095		914-972	865-914	745	355	630
15	14		43	4	1440-1525		1402-1440	1383-1402	1357-1383		1287-1357	1095-1287	1032-1095		950-1032	765	410	740
11	15		64	4	1380-1432		1329-1380	1318-1329	1290-1318		1202-1290	1111-1202		1045-1111	995-1045	150	340	1255
	16																	

APPENDIX E

DERIVED TRANSIT SCHEDULE

TABLE XVI

LIST OF VESSELS IN READY TIME ORDER

Direction	Ready time	Beam	No. of Locos Required	Remarks
Northbound				
1	-760 mins.	27 ft.	4	CC/DL
2	-455	64	4	
3	-220	56	4	MF (W-180
4	-165	60	4	(E-0
5	-140	71	4	
6	-100	75	4	
7	05	90	6	DL
8	35	56	4	PM (W-120
9	70	105	6	CC/DL (E-0
10	110	64	4	
11	300	71	4	
12	305	64	4	DL
13	330	62	4	
14	480	84	4	
15	480	51	4	
16	535	63	4	
Southbound				
1	-840 mins.	85 ft.	6	DL
2	-620	88	6	DL
3	-190	101	6	CC/DL
4	-180	60	4	(W-180
5	-60	61	4	Gatun (E-180
6	60	62	4	
7	60	80	6	
8	90	72	4	
9	120	62	4	
10	120	64	4	
11	180	64	4	
12	300	64	4	
13	675	84	6	
14	745	63	4	CC
15	765	43	4	

TABLE XVII. DERIVED SCHEDULE (NORTHBOUND)

NORTHBOUND/~~SOUTHBOUND~~ SCHEDULING FORM

R.T. ORD.	TR. ORD.	REMARKS	BEAM	LOCOS	PACIFIC CHANNEL	MF LOCK E(6)	MF LOCK W(4)	MF LAKE	PM LOCK E(6)	PM LOCK W(4)	CUT	GATUN LAKE	GATUN LOCK E(6)	GATUN LOCK W(4)	ATLANTIC CHANNEL	R.T.	I.T. TIME	CZW TIME
2	1		64	4	-60-0	0-40		40-65	65-95		95-155	155-275		275-330	330-360	-455	330	815
3	2		56	4	-10-50	50-90		90-110	110-140		140-200	(20) 200-320		340-390	390-420	-220	340	640
4	3		60	4	35-95	95-135		135-160	160-190		190-250	(30) 250-370		400-455	455-485	-105	360	650
5	4		71	4	85-145	145-190		190-215	215-245		245-365	(40) 305-425		465-525	525-555	-140	350	695
6	5		75	4	120-180		180-225	225-250		250-280	280-340	(75) 340-460		535-575	575-625	-120	415	725
8	6		56	4	140-200	200-240		240-260	260-290		290-350	(135) 350-470		605-655	655-685	35	455	600
10	7		64	4	175-235		235-275	275-300		300-330	330-390	(155) 390-510		665-720	720-750	110	435	640
1	8	CC/DL	27	4	300-360	360-395		395-415	(105) 415-445		550-610	(40) 610-730	770-820		820-850	700	410	1610
9	9	CC/DL	105	6	340-400	400-475		475-505	505-560		560-620	(90) 620-740	830-920		920-950	70	515	850
7	10	DL	90	6	425-485	485-545		545-570	570-610		610-670	(140) 670-790	930-1000		1000-1030	05	510	1025
12	11	DL	64	4	495-555	555-595		595-620	620-650		650-710	(45) 710-830		925-950	950-1010	305	425	705
11	12		71	4	545-605	605-650		650-665		665-705	705-765	(105) 765-885		990-1050	1050-1090	300	445	730
13	13		62	4	600-660	660-700		700-725		(95) 725-755	800-910	(50) 910-1030		1060-1115	1115-1145	330	455	815
14	14		54	4	630-690		690-740	740-765		(60) 765-800	860-920	(85) 920-1040		1125-1190	1190-1220	450	500	740
15	15		51	4	690-750		750-790	790-810		(30) 810-840	870-930	(130) 930-1050		1200-1250	1250-1280	480	500	800
16	16		63	4	740-800		800-840	840-865		865-895	895-955	(155) 955-1075		1260-1315	1315-1345	535	515	810

TABLE XVIII. DERIVED SCHEDULE (SOUTHBOUND)

~~NORTHBOUND~~/SOUTHBOUND SCHEDULING FORM

R.T. ORD.	TR. ORD.	REMARKS	BEAM	LOCOS	PACIFIC CHANNEL	MF LOCK E(6)	MF LOCK W(4)	MF LAKE	PM LOCK E(6)	PM LOCK W(4)	CUT	GATUN LAKE	GATUN LOCK E(6)	GATUN LOCK W(4)	ATLANTIC CHANNEL	R.T.	I.T. TIME	CZW TIME
4	1		60	4	515-565		475-515	450-475		420-450	355-420	235-355	180-235		120-180	-180	335	745
5	2		61	4	565-615		(10) 515-565	490-515		([illegible]) 430-4[illegible]	365-430	245-365		190-245	130-190	-60	375	675
6	3		62	4	615-665		(20) 555-615	[illegible]-555		(15) 4[illegible]-5[illegible]	420-4[illegible]	300-420	245-300		185-245	60	370	605
7	4		80	6	805-855	755-805		730-755	695-730		630-695	(135) 375-495	310-375		250-310	60	495	795
1	5	DL	85	6	865-915	(15) 800-865		775-800	([illegible]) 720-775		640-705	(70) 450-570	385-450		325-385	-840	480	1755
2	6	DL	88	6	925-975	(30) 845-925		820-845	(70) 715-820		650-715	(5) 525-645	460-525		400-460	-620	465	1595
3	7	CC/DL	101	6	1010-1060	(10) 925-1010		895-925	840-895		775-840	(30) 625-745	535-625		475-535	-190	475	1250
8	8		72	4	1005-1055		960-1005	935-960	(25) 880-935		815-880	695-815	635-695		575-635	40	370	965
9	9		62	4	1055-1105		(15) 1000-1055	975-1000	945-975		880-945	760-880	705-760		645-705	120	350	985
10	10		64	4	1065-1115	1025-1065		1000-1025		970-1000	905-970	785-905		730-785	670-730	120	335	995
11	11		64	4	1130-1180	1090-1130		1065-1090	1035-1065		970-1035	850-970		795-850	735-795	180	335	1000
12	12		64	4	1195-1245	1155-1195		1130-1155	1100-1130		1035-1100	915-1035		860-915	800-860	300	335	945
13	13		84	6	1370-1420	1320-1370		1295-1320	1260-1295		1195-1260	1075-1195	1010-1075		950-1010	675	335	745
14	14	CC	63	4	1420-1470	1380-1420		1355-1380	1325-1355		1260-1325	1140-1260	1085-1140		1025-1085	745	335	725
15	15		43	4	1485-1535	1445-1485		1420-1445	1390-1420		1325-1390	1205-1325	1150-1205		1040-1150	765	335	770
	16																	

LIST OF REFERENCES

1. Panama Canal Company, Marine Traffic Control Manual, 1971.

2. U.S. Atlantic-Pacific Interoceanic Canal Study Commission, Interoceanic Canal Studies, 1970.

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This thesis presents an algorithm for scheduling vessel transits through the Panama Canal together with a compilation of current Marine Traffic Control scheduling practices. The performance of the scheduling algorithm is compared with the results of an actual transit schedule using the Panama Canal Company Marine Traffic Control scheduling objectives and additional measures of effectiveness derived in this paper.

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The interaction between these measures of effectiveness is discussed as pertains to their future use in the efficient scheduling of vessels through the canal.

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